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STUDENT WORKBOOK

SOILS ENGINEERING

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D103.120:

SOILS ENGINEERING

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TABLE OF CONTENTS

	PAGE
CALIFORNIA BEARING RATIO	1
SOILS STABILIZATION	43
SOILS EXPLORATION	82
COMPUTER AIDED INSTRUCTION (CAI)	84
ANSWERS TO PRACTICAL EXERCISES	91

REFERENCES

TM 5-330, Sept1968 w/ C1. Planning and Design of Roads, Airbases, and Heliports in the Theater of Operations.

TM 5-530, Feb 1971. Materials Testing.

TM 5-822-4, Apr 1983. Soil Stabilization for Pavements.

Instructor Report S-74-3, Sept 1974, Waterways Experiment Station. Stabilization of Soil and Aggregate Materials for Forward Area Operations.

CALIFORNIA BEARING RATIO

I. INTRODUCTION

A. History: During the early 1940's, the responsibility for the design and construction of military roads and airfields was assigned to the Corps of Engineers. Later, the Corps was delegated the same function pertaining to civil airfields and roads required for military use. After deliberation, the principles then used by the California Highway Department, known as the California Bearing Ratio Method (CBR) were adopted for the design of flexible pavements. Since 1940, the Corps has been involved in continued investigations relative to flexible pavement design in the areas of development, validation, and revision. Although the CBR method of design is considered a semi-empirical approach where each of the factors relating to a soil's ability to resist traffic loads have not been individually analyzed, its worth as a design method lies in the fact that over 35 years of experience with actual pavement structures have provided the basis for our present design curves.

B. Definition: CBR is an index of the shearing resistance of soil, obtained by forcing a steel piston having a three square inch end area into the soil at a rate of 0.05 inches per minute and measuring the force required to achieve 0.1 and 0.2 inches of penetration. The force obtained is ratioed against standard test values of 3000 and 4500 pounds for a standard crushed limestone (one which passes the 3/4 inch sieve and is well graded).

EQUATION 1.

$$\text{CBR RATIO} = \frac{\text{ACTUAL SOIL STRESS}}{\text{STRESS OF STANDARD}} \times 100$$

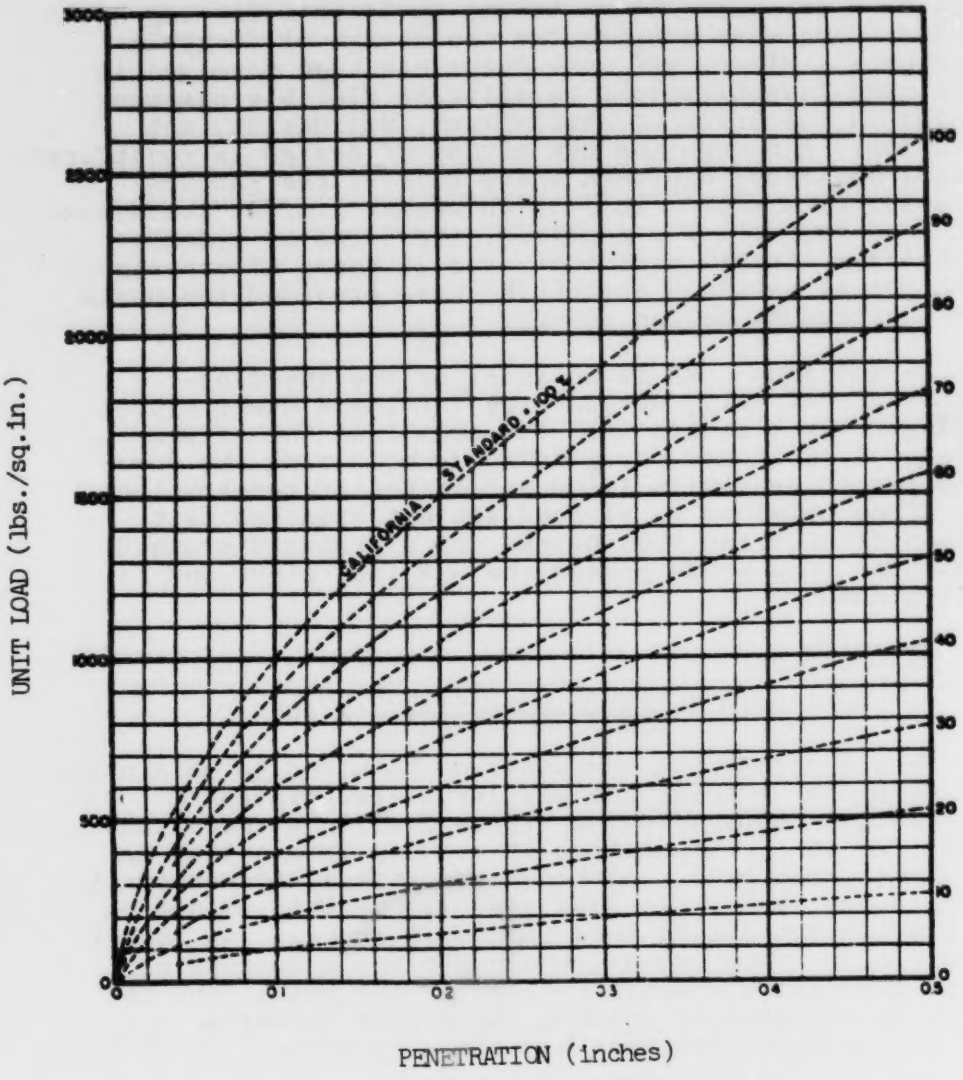
To illustrate the computations required to obtain the CBR value for a soil, the results of two typical penetration tests shown on Figure 2 will be used. The curve "A" is representative of results from a test in which all went well. Although the stress vs. penetration plot is not linear, it does approximate this condition at penetration depths less than 0.30 inches. At larger penetration depth values, the curve has a decreasing slope indicating plastic failure of the soil. The CBR value is computed by reading the stress values at 0.1 and 0.2 inch penetrations and using equation 1 as follows:

CBR (0.1) = (200/1000) X 100 = 20%

CBR (0.2) = (345/1500) X 100 = 23%

FIGURE 1.

CALIFORNIA BEARING RATIO TEST GRAPH
(Plot test curve below to obtain corrected unit load)



The next question that arises is which value should be used. The larger of the two values is used, but if CBR (0.2) is larger it must first be verified by testing another sample.

The selection criteria imply that:

(1) Strengths used to design a pavement will be measured at no more than 0.2 inches of soil deformation.

(2) If CBR (0.1) is greater than CBR (0.2), the soil has begun plastic*failure between these limits of deformation and soil strengths obtained at plastic failure will not be used.

(3) If CBR (0.2) is greater than CBR (0.1), the soil is still undergoing elastic*deformation up to 0.2 inches of penetration and that this elastic strength can be verified by a second test.

In the preceding example, the appropriate CBR would be 23% if it is verified by a second test.

*Plastic failure is when a substance undergoes permanent deformation without rupturing.

*Elastic deformation is a temporary change in shape, due to an applied force, which permits the substance to return to its original shape when the force is removed.

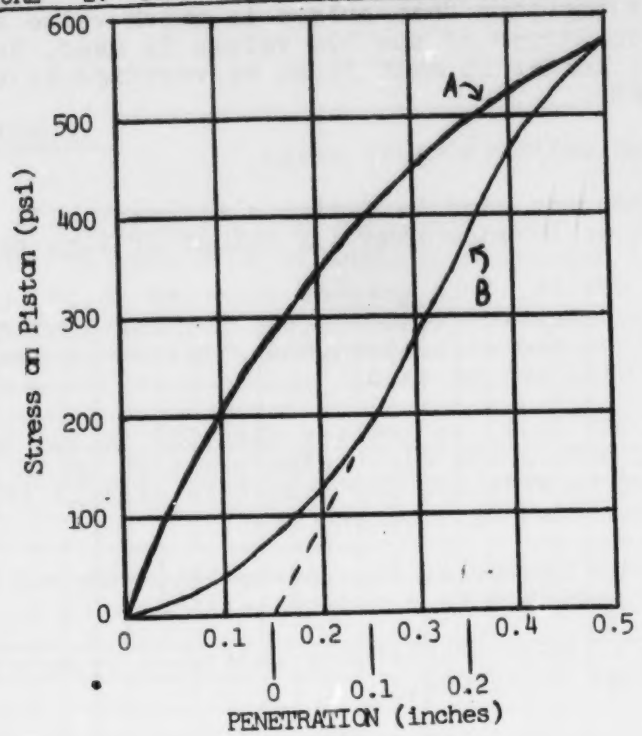
Curve "B" in Figure 2, which has a concave upward shape between 0 and 0.23 inches penetrations, is a manifestation of surface irregularities result ng from the lack of complete initial contact between the piston and the soil sample surface. Compensation for this fault can be made by extending the straight line portion of the stress/penetration curve until it intersects the abcissa and taking that intersection as the new origin. The stresses at the new 0.1 and 0.2 inch penetrations are shown in Figure 2. The CBR values are computed by using equation 1, below. Selection of the specific CBR is made using the same criteria as for curve "A".

CBR (0.1) = (190/1000) X 100 = 19%

CBR (0.2) = (375/1500) X 100 = 25%

The appropriate value would be 25% if the test were verified. After a CBR value has been determined from the penetration data, that value by convention is referred to as a "corrected CBR", whether or not an adjustment to the original has been made.

FIGURE 2. TYPICAL CBR PENETRATION TEST RESULTS



C. FLEXIBLE PAVEMENT CONSIDERATIONS

Subgrade - The in-place natural soil which supports the pavement structure. It may have a CBR value ranging from almost 0 to 100%, and specifications may require that portions of it be compacted.

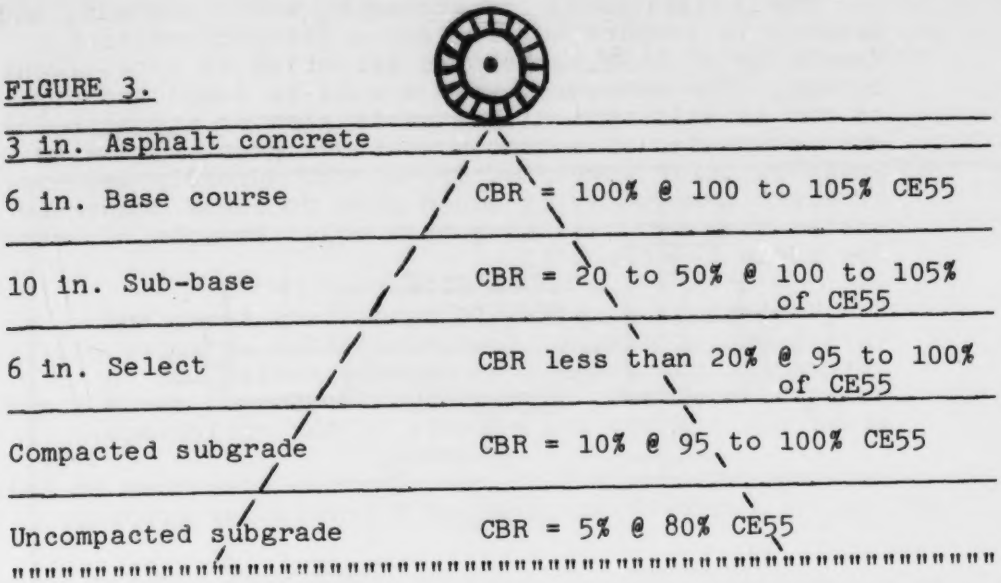
Select material - A naturally occurring imported soil having CBR values less than 20% but greater than the compacted subgrade. It is used to carry stress levels intermediate to those supported by the subgrade and sub-base material.

Sub-base material - Imported cohesionless material having CBR values ranging from 20% to 50%. It is normally obtained from natural gravel deposits and serves to carry intermediate stresses in the pavement.

Base course - Highest quality structural material having strengths near that of the CBR standard material. For pavement design, CBR values are normally assigned based on gradation requirements rather than CBR tests. Base courses are always cohesionless and are usually processed to obtain the desired gradation.

Asphalt concrete - Material that serves primarily as a wearing course and moisture barrier.

FIGURE 3.


3 in. Asphalt concrete
6 in. Base course
CBR = 100% @ 100 to 105% CE55
10 in. Sub-base
CBR = 20 to 50% @ 100 to 105% of CE55
6 in. Select
CBR less than 20% @ 95 to 100% of CE55
Compacted subgrade
CBR = 10% @ 95 to 100% CE55
Uncompacted subgrade
CBR = 5% @ 80% CE55

D. SELECTION OF A TEST PROGRAM

The type of test program and the analysis of the resulting data depends to a considerable degree on where the soil is going to be used in the pavement, whether or not the soil will be disturbed during the construction process, the level of compactive effort required to preclude settlement, and the physical nature of the soil. From Figure 3 it can be seen that the materials above the uncompacted subgrade will undergo considerable disturbance, and the laboratory tests used to define strength must simulate this disturbance. Likewise, a test method that gives strengths for undisturbed samples should be used for the uncompacted subgrade. The effect of density must be included in the evaluation of the compactive effort corresponding to those required by compaction specifications. Lastly, the nature of the soil will determine the amount and type of laboratory work required. For example, coarse-grained, free-draining soils or those soils having few fines may display little strength variation with changes in moisture content while some fine-grained soils show objectionable volumetric changes (swelling) as the molding moisture content varies. Table 2 on Page 15 is a summary of the test methods which should serve as a guide for the following discussion. However, the basic principle underlying this categorization is simulation of the conditions to which a soil is subjected during both construction and the life of the structure.

The following facts should be kept in mind when developing a test program:

1. An increase in compactive effort produces an increase in density and a decrease in OMC(where OMC is the optimum moisture content at a specified compaction).

2. The relationship of strength, water content, and density is complex but follows a distinct pattern. Knowledge of this pattern is essential to intelligent design. For instance, when a soil is compacted dry of OMC it will typically exhibit greater strength than when compacted at moisture contents greater than OMC. However, soils compacted dry of OMC normally lose more strength when water is added than do soils compacted wetter than OMC, assuming that equal amounts of water are added to each soil.

3. Variations of blows in laboratory tests and variations of passes, foot sixe, tire pressure, lift thickness, and gross load produce variations in compactive effort. Proper application of facts 1 and 2 above can predict the effects of the variations.

The engineer may modify the programs described in this text to fit the special needs of a particular project.

II. IN-PLACE TESTS

A. Field CBR testing

As a part of flexible pavement design, it will be necessary to determine the strength of the subgrade soil at its natural density. To accomplish this, the CBR penetration apparatus can be mounted on a vehicle from which the penetration test can be performed in a manner similar to the laboratory method. In-place tests are used for design under any one of the following conditions:

(1) The in-place density and moisture content are such that the degree of saturation is 80%.
(2) The soil is coarse-grained and cohesionless so that it is not affected by changes in water content(it is a free-draining soil).
(3) The soil has been in place for several years so that fluctuation in moisture content is minimal(the soil must have been undisturbed for at least three years). This applies to road construction over an old fill site.

B. Undisturbed sample* testing

A shortcoming of the field CBR thst is that the swell o of a soil cannot be monitored. Additionally, its loss of strength upon saturation cannot be determined. If the engineer needs in-situ CBR design values for soils which may be prone either to swell or to lose much of their bearing capacity upon saturation, he may use the "undisturbed sample" test. For this test, a sampling collar is affixed to the CBR mold and the mold is slowly forced into the soil. The test is only used on cohesive soils, and is further described in TM 5-530.

*Driving the CBR mold into the soil will actually cause some disturbance. Care must be taken to insure that this disturbance is held to a minimum. "Non-remolded is a more accurate description of this procedure than is "undisturbed".

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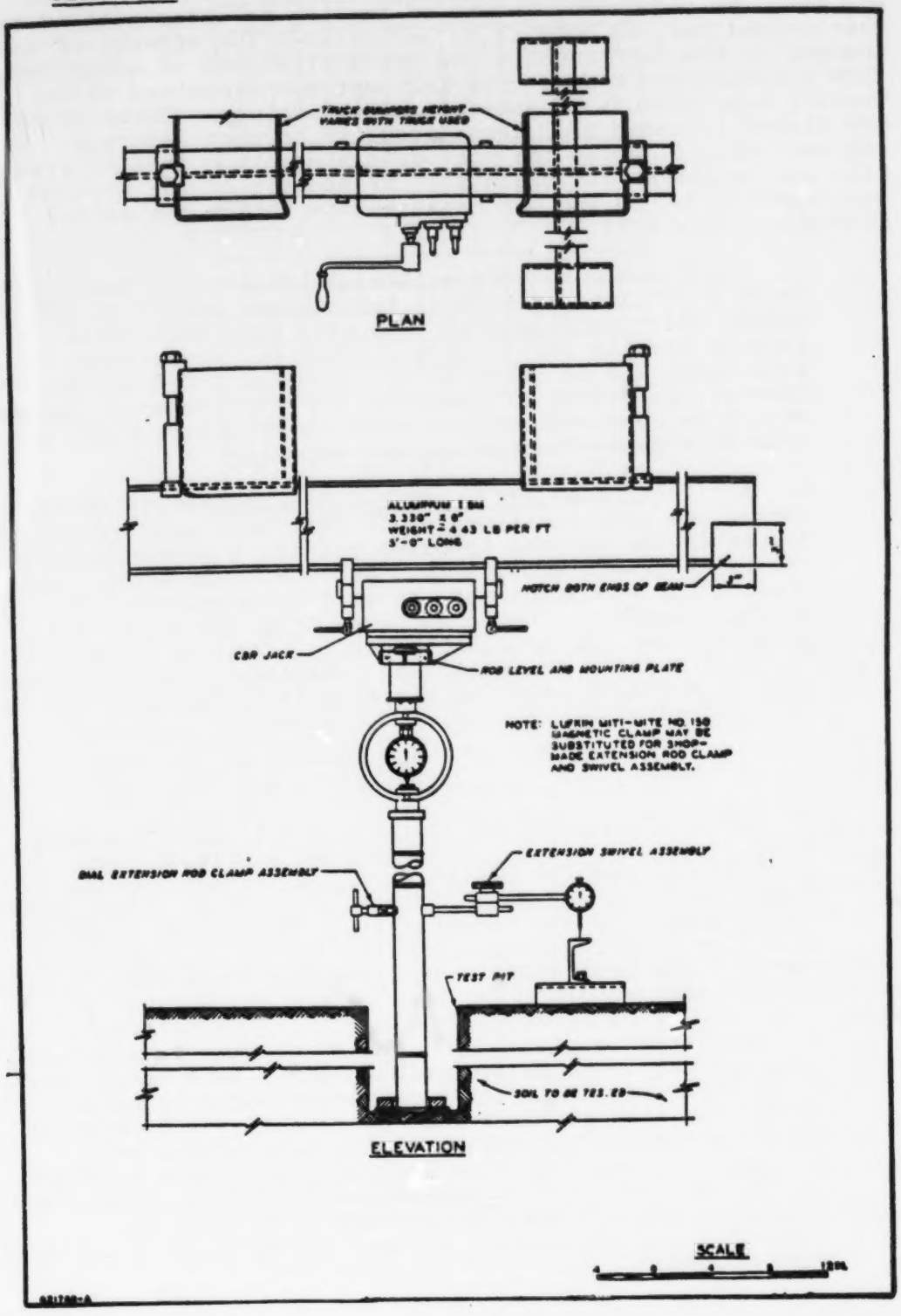
FIGURE 4.


TRUCK BUMPERS HEIGHT VARIES WITH TRUCK USED
PLAN
ALUMINUM I BM
3.330" x 6"
WEIGHT = 4.43 LB PER FT
3'-0" LONG
NOTCH BOTH ENDS OF BEAM
CBR JACK
ROD LEVEL AND MOUNTING PLATE
NOTE: LUFKIN MITI-MITE NO 150 MAGNETIC CLAMP MAY BE SUBSTITUTED FOR SHOP-MADE EXTENSION ROD CLAMP AND SWIVEL ASSEMBLY.
EXTENSION SWIVEL ASSEMBLY
DIAL EXTENSION ROD CLAMP ASSEMBLY
TEST PIT
SOIL TO BE TESTED
ELEVATION
SCALE

III. EXPEDIENT TESTS

The tactical situation in the Theater of Operations may preclude a full range of CBR tests as described above. The engineer may reduce the amount of testing or alter some of the test procedures, as long as he understands the effects of the changes on the test results and the limitations of using results from non-standard tests. The test methods described below present some methods of determining CBR values. These procedures are listed in order from least accurate to most accurate. The engineer should choose the most accurate method available within time and equipment constraints. The success of the mission is contingent upon how the CBR measurements depict the actual strength of the soil.

A. Correlation to USCS soil classification. Table 2-4 in TM 5-330(Table 3 in this text) gives ranges of CBR values which correlate to each soil type(USCS class). When no testing method is available the lower value in this range may be taken as an approximate CBR value. However, no design of permanent or semi-permanent pavement should be done without testing. These values might serve only as a guide for preliminary planning.

B. Airfield Index (AI). TM 5-330 describes in detail the use of the cone penetrometer to determine an airfield index. Generally the process involves pushing a penetrometer(from the soils trafficability test set) into the ground and reading the resistance of the soil to penetration at various depths. Readings should be taken from the penetrometer gauge at even depths(2,4,6inches...) down to 24 inches. The dial reading is called the cone index and is converted into an airfield index by dividing it by the cone end area (in hundredths of an inch). For example:

AI = cone index/50 for the 0.5 sq.in. cone

AI = cone index/20 for the 0.2 sq.in. cone

The airfield indices are averaged to give a single value at one location. This average airfield index can be converted to CBR for design purposes through the use of Figure 2-17 from TM 5-330 (Figure 5), shown below. These values generally are conservative. Penetrometer tests should be made randomly along the length of a proposed runway. The lowest CBR value computed would then be used for the design.

C. Simulated in-place CBR. The first step in simulated in-place CBR is to determine the most likely conditions to be expected. This can range from soaked to arid conditions, and is determined by an analysis of samples taken from the site, and by the climate of the area. The best likely projection must be made. Both moisture content and dry density determinators are important, and are taken from an undisturbed sample, or from the largest chunk available. Volumes may have to be estimated when necessary.

FIGURE 5.

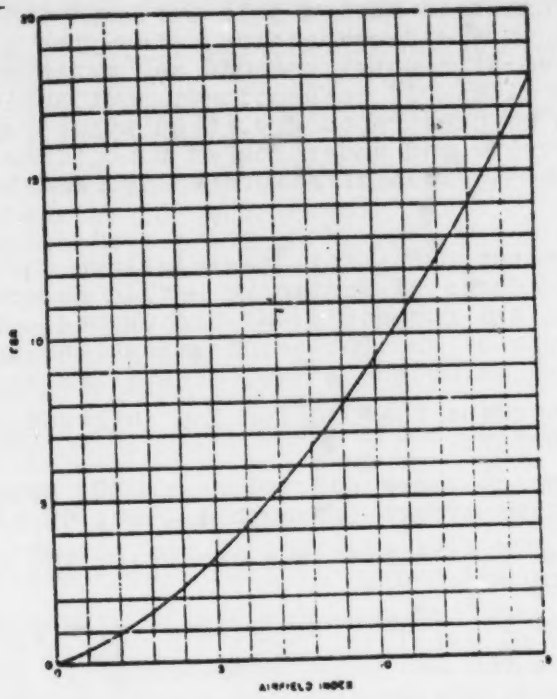


Figure 2-17. Correlation of CBR versus airfield index.

Once the in-place conditions have been determined, the analyst must attempt to duplicate them in the laboratory with the remainder of the sample. Moisture content can be controlled through accurate addition of water, while estimates must be made of density. Two samples may be necessary for density duplication, trying one compactive effort, and adjusting based upon what density is calculated.

CBR testing should be conducted on the duplicated sample, using normal penetration procedures. The analyst must mark the appropriate boxes on the worksheet(DD Form 1212) for soaked or unsoaked conditions. The CBR value determined will approximate the strength of the soil when in the same state as that of the sample.

Further testing may be conducted on the tested sample to approximate anticipated conditions. This predicted condition may be a field observation or long range forecast.

D. One-point test. This test follows the same procedures as described previously, except that only one mold is compacted. This is done in the following manner:

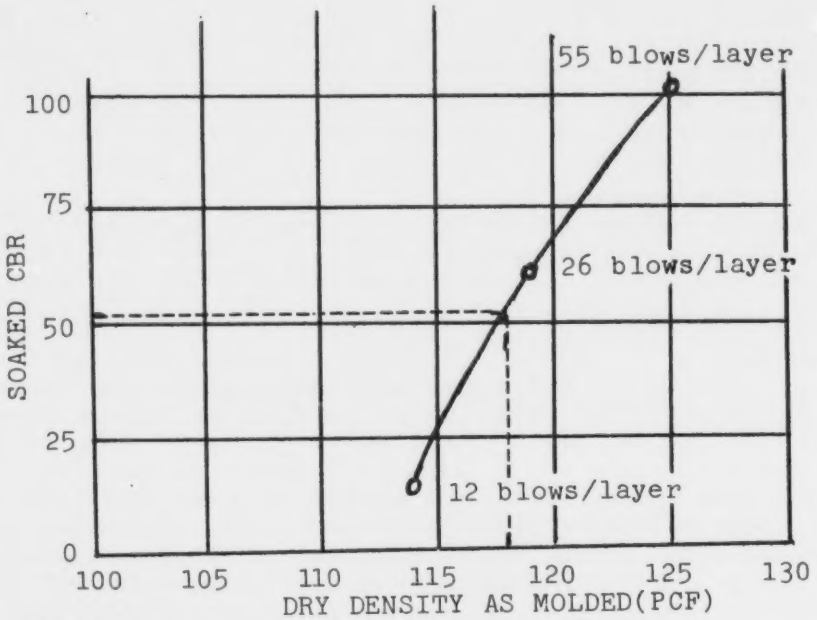
1. Determine the OMC and CE55 maximum dry density.
2. Compact one mold at this density and OMC.
3. Soak and penetrate the mold in the standard way.
4. Record the CBR value.

Note that this method does not take into account variations in field compaction, since the soil will never be compacted at exactly the OMC and maximum dry density on the job site. If saturation is not anticipated, the sample can be penetrated dry, then soaked and penetrated on the opposite end under soaked conditions. This will provide a comparison of saturated vs. moist strengths of the soil.

E. Three-point CBR. This test follows the same procedure used in the Corps of Engineers method except that only three molds are compacted and penetrated. Generally the test consists of the following variations on the Corps of Engineers method:

1. Determine the OMC for the soil and the CE55 maximum dry density.
2. Compact three CBR molds at OMC, varying the compactive effort for each(12, 26, 55 blows/layer).
3. Soak the samples and penetrate the molds in the standard way.
4. Plot the soaked CBR values vs. dry density.
5. Find the CBR which corresponds to the minimum acceptable dry density for the project(i.e. 96% CE55 maximum dry density) as shown below.

FIGURE 6.



EXAMPLE:
Given CE55 max dry density=124 pcf.
Find the CBR at 95% of CE55 max dry density.
Answer: 95% X 124 pcf = 117.8 pcf. At 117.8 pcf, the CBR is 52.

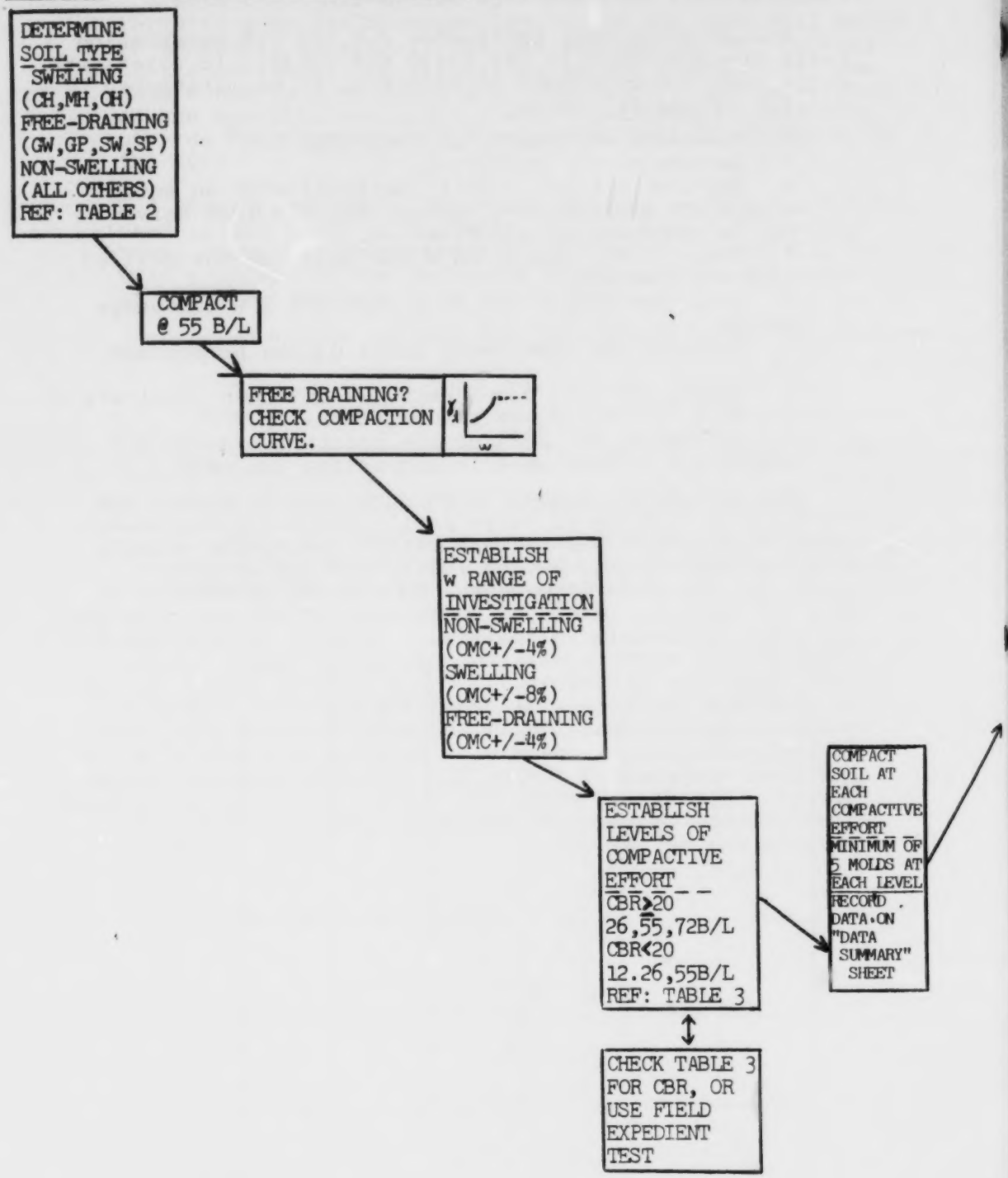
IV. A typical CBR penetration test.

The detailed test procedures for the CBR penetration tests are contained in TMs 5-330 and 5-530. In brief, the steps that are performed on each mold to be penetrated consist of the following:

1. Oven-dry the sample at less than 140° F.
2. Determine the gradation.
3. Replace all 3/4 inch(+) material with an equal weight of material that passes the 3/4 inch seive but is retained on the #4 seive.
4. Compact the sample in a CBR mold, at the desired moisture content.
5. Soak the sample for four days using a surcharge weight.
6. Compute the free swell index or the percentage of swell.
7. Drain the mold for 15 minutes and then penetrate it.
8. Plot the stress-strain relationship.
9. Determine the CBR for the moisture content and compactive effort used in compacting the mold.

The objective of steps 1 through 3 is to reduce the bridging or wedging of large particles in the CBR mold, which could cause non-representative compaction results and high CBR values, due to relative sizes of piston, particle, and mold diameters. In step 4, an attempt is made to simulate levels of compactive effort and moisture contents obtainable in the field. Step 5 is intended to simulate the worst condition that could happen to the soil (complete saturation). The surcharge weight is used to simulate the effect of overlying pavement layers on the soil's strength. It is important to note that many of the procedural steps are of an arbitrary nature which has been compensated for in the flexible pavement design curves. Because of this, the standardized test procedures given in the TMs must be followed precisely or the test results may be invalid.

FIGURE 7. CBR TESTING PROGRAM FLOW CHART



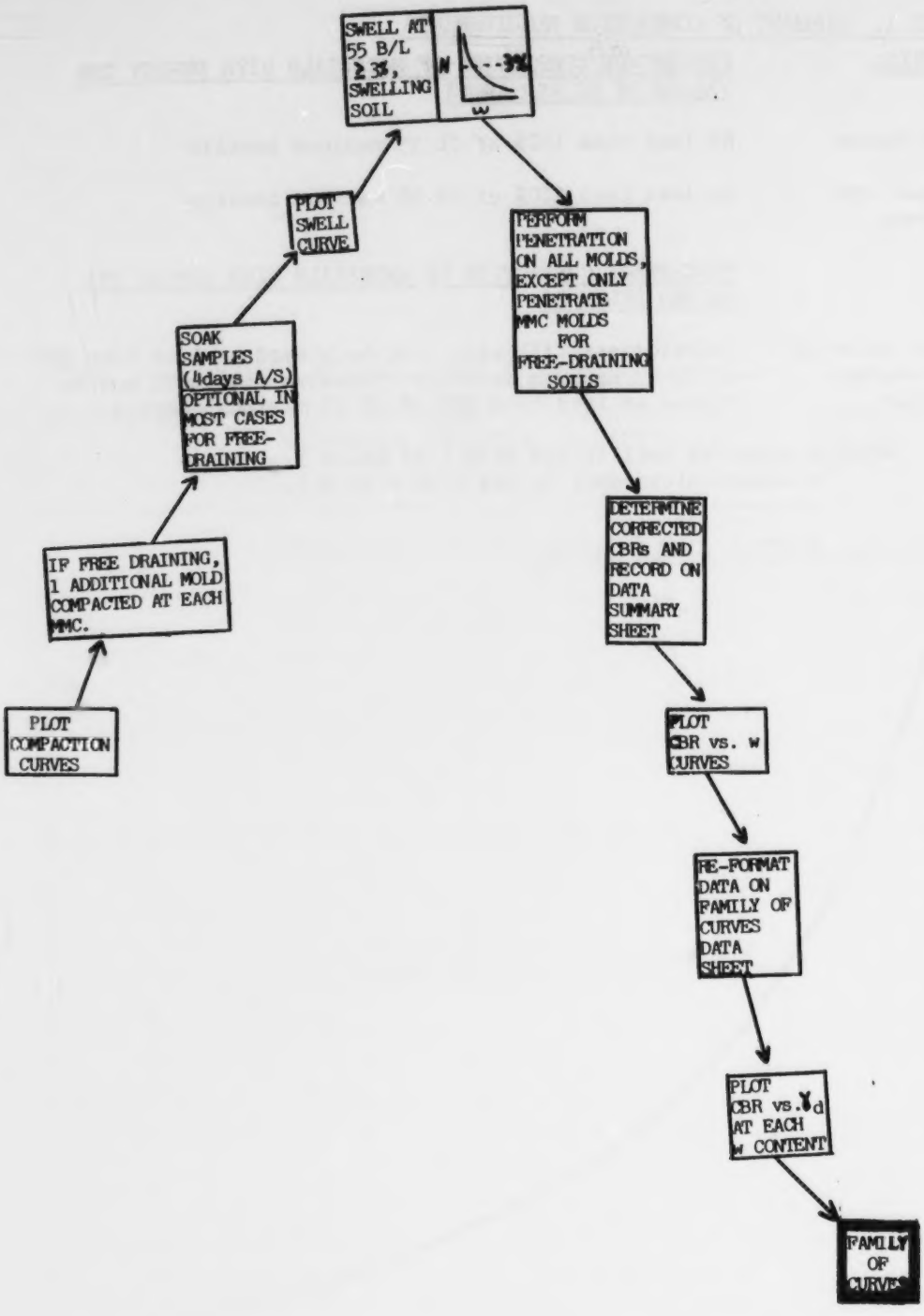

SWELL AT 55 B/L ≥ 3%, SWELLING SOIL
N
3%
w
PLOT SWELL CURVE
SOAK SAMPLES (4days A/S) OPTIONAL IN MOST CASES FOR FREE-DRAINING
IF FREE DRAINING, 1 ADDITIONAL MOLD COMPACTED AT EACH MMC.
PLOT COMPACTION CURVES
PERFORM PENETRATION ON ALL MOLDS, EXCEPT ONLY PENETRATE MMC MOLDS FOR FREE-DRAINING SOILS
DETERMINE CORRECTED CBRs AND RECORD ON DATA SUMMARY SHEET
PLOT CBR vs. w CURVES
RE-FORMAT DATA ON FAMILY OF CURVES DATA SHEET
PLOT CBR vs. γd AT EACH w CONTENT
FAMILY OF CURVES

TABLE 1. SUMMARY OF COMPACTION REQUIREMENTS

MATERIAL	PERCENTAGE COMPACTION OF MATERIALS WITH DESIGN CBR VALUES OF 20 AND ABOVE
Base Course	No less than 100% of CE 55 maximum density
Subbase and Subgrade	No less than 100% of CE 55 maximum density
	PERCENTAGE COMPACTION OF MATERIALS WITH DESIGN CBR VALUES BELOW 20
Select material and subgrade in fills	Cohesionless fill will not be placed at less than 95% of CE 55 maximum density. Cohesive fill will not be placed at less than 90% of CE 55 maximum density.

NOTE: A cohesive soil is one with a PI above 5.
A cohesionless soil is one with a PI ≤ 5.

FIGURE 8. SAMPLE SWELL CURVE.

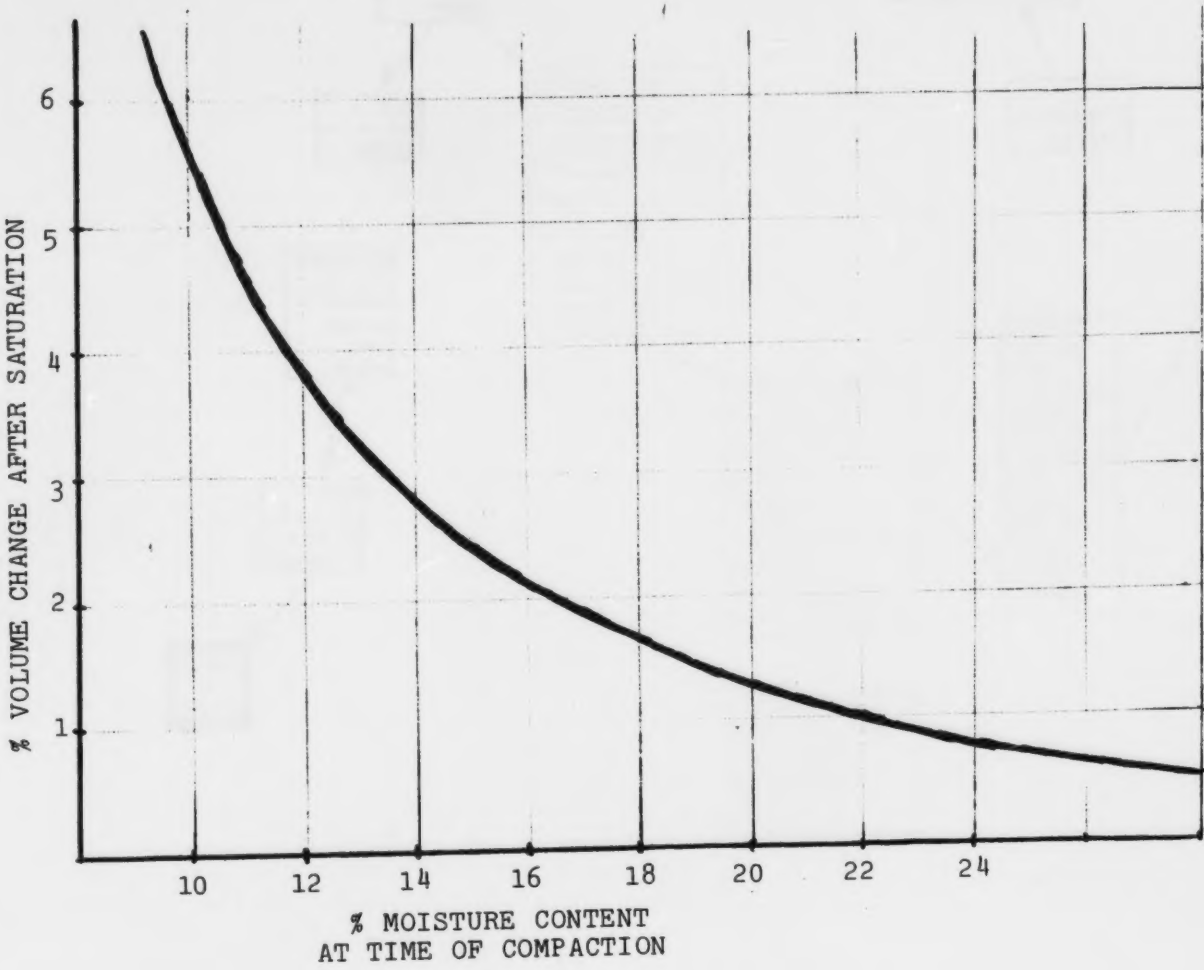


TABLE 2. SUMMARY OF CBR TEST PROGRAMS

TEST PROGRAM	TYPE OF SOIL NORMALLY TESTED*	COMPACTION BLOWS/LAYER	PROBABLE USE OF TEST RESULTS
	REMOLDED LABORATORY TESTS		
Non-swelling soils	All except CH, MH,OH,GW,GP,SW, and SP.	For CBR 20, use 26,55,72. For CBR 20, use 12,26,55.	For compacted subgrade, select, and sub-base material.
Swelling soils	CH,MH, and OH.	12,26,55.	Low quality compacted subgrades.
Free-draining soils	GW,GP,SW,and SP.	26,55,72.	Compacted subgrade, select, and sub-base.
	TESTS FOR IN-SITU STRENGTHS		
Field CBR	All	N/A	Uncompacted subgrade,
Undisturbed sample.	CH,MH, and OH.	N/A	Uncompacted subgrade- allows for evaluation of swell.

*This categorization is intended to serve as a guide for planning laboratory activities. Deviations may be noted in the initial stages of a test program which will dictate adjustments.

TABLE 3. CHARACTERISTICS PERTINENT TO ROADS AND AIRFIELDS

CORPS OF ENGINEERS

Major Divisions (1)	(2)	Symbol: Letter (3)	Symbol: Hatching (4)	Symbol: Color (5)	Name (6)	Value as Subgrade When Not Subject to Frost Action (7)	Value as Subbase When Not Subject to Frost Action (8)
COARSE-GRAINED SOILS	GRAVEL AND GRAVELLY SOILS	GW		Red	Well-graded gravels or gravel-sand mixtures, little or no fines	Excellent	Excellent
		GP		Red	Poorly graded gravels or gravel-sand mixtures, little or no fines	Good to excellent	Good
		GM d		Yellow	Silty gravels, gravel-sand-silt mixtures	Good to excellent	Good
		GM u		Yellow	Silty gravels, gravel-sand-silt mixtures	Good	Fair
		GC		Yellow	Clayey gravels, gravel-sand-clay mixtures	Good	Fair
	SAND AND SANDY SOILS	SW		Red	Well-graded sands or gravelly sands, little or no fines	Good	Fair to good
		SP		Red	Poorly graded sands or gravelly sands, little or no fines	Fair to good	Fair
		SM d		Yellow	Silty sands, sand-silt mixtures	Fair to good	Fair to good
		SM u		Yellow	Silty sands, sand-silt mixtures	Fair	Poor to fair
		SC		Yellow	Clayey sands, sand-clay mixtures	Poor to fair	Poor
FINE-GRAINED SOILS	SILTS AND CLAYS LL IS LESS THAN 50	ML		Green	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity	Poor to fair	Not suitable
		CL		Green	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	Poor to fair	Not suitable
		OL		Green	Organic silts and organic silt-clays of low plasticity	Poor	Not suitable
	SILTS AND CLAYS LL IS 50 or greater	MH		Blue	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	Poor	Not suitable
		CH		Blue	Inorganic clays of high plasticity, fat clays	Poor to fair	Not suitable
		OH		Blue	Organic clays of medium to high plasticity, organic silts	Poor to very poor	Not suitable
HIGHLY ORGANIC SOILS		Pt		Orange	Peat and other highly organic soils	Not suitable	Not suitable

Note:

1. Column 3, division of GM and SM groups into subdivisions of d and u are for roads and airfields only. Subdivision is on basis of Atterberg plasticity index is 5 or less; the suffix u will be used otherwise.
2. In column 13, the equipment listed will usually produce the required densities with a reasonable number of passes when moisture conditions and are listed because variable soil characteristics within a given soil group may require different equipment. In some instances, a combination
   a. Processed base materials and other angular materials. Steel-wheeled and rubber-tired rollers are recommended for hard, angular materials subject to degradation.
   b. Finishing. Rubber-tired equipment is recommended for rolling during final shaping operations for most soils and processed materials.
   c. Equipment size. The following sizes of equipment are necessary to assure the high densities required for airfield construction:
      Crawler-type tractor -- total weight in excess of 30,000 lb.
      Rubber-tired equipment -- wheel load in excess of 15,000 lb, wheel loads as high as 40,000 lb may be necessary to obtain the required
      Sheepsfoot roller -- unit pressure (on 6- to 12-sq-in. foot) to be in excess of 250 psi and unit pressures as high as 650 psi may be
      be at least 5 per cent of the total peripheral area of the drum, using the diameter measured to the faces of the feet.
3. Column 14, unit dry weights are for compacted soil at optimum moisture content for modified AASHO compaction effort.
4. In column 15, the maximum value that can be used in design of airfields is, in some cases, limited by gradation and plasticity requirements.

Value as Base When Not Subject to Frost Action (9)	Potential Frost Action (10)	Compressibility and Expansion (11)	Drainage Characteristics (12)	Compaction Equipment (13)	Unit Dry Weight lb per cu ft (14)	Typical Design Values	
						CBR (15)	Subgrade Modulus k lb per cu in. (16)
Good	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired roller, steel-wheeled roller	125-140	40-80	300-500
Fair to good	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired roller, steel-wheeled roller	110-140	30-60	300-500
Fair to good	Slight to medium	Very slight	Fair to poor	Rubber-tired roller, sheepsfoot roller; close control of moisture	125-145	40-60	300-500
Poor to not suitable	Slight to medium	Slight	Poor to practically impervious	Rubber-tired roller, sheepsfoot roller	115-135	20-30	200-500
Poor to not suitable	Slight to medium	Slight	Poor to practically impervious	Rubber-tired roller, sheepsfoot roller	130-145	20-40	200-500
Poor	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired roller	110-130	20-40	200-400
Poor to not suitable	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired roller	105-135	10-40	150-400
Poor	Slight to high	Very slight	Fair to poor	Rubber-tired roller, sheepsfoot roller; close control of moisture	120-135	15-40	150-400
Not suitable	Slight to high	Slight to medium	Poor to practically impervious	Rubber-tired roller, sheepsfoot roller	100-130	10-20	100-300
Not suitable	Slight to high	Slight to medium	Poor to practically impervious	Rubber-tired roller, sheepsfoot roller	100-135	5-20	100-300
Not suitable	Medium to very high	Slight to medium	Fair to poor	Rubber-tired roller, sheepsfoot roller; close control of moisture	90-130	15 or less	100-200
Not suitable	Medium to high	Medium	Practically impervious	Rubber-tired roller, sheepsfoot roller	90-130	15 or less	50-150
Not suitable	Medium to high	Medium to high	Poor	Rubber-tired roller, sheepsfoot roller	90-105	5 or less	50-100
Not suitable	Medium to very high	High	Fair to poor	Sheepsfoot roller, rubber-tired roller	80-105	10 or less	50-100
Not suitable	Medium	High	Practically impervious	Sheepsfoot roller, rubber-tired roller	90-110	15 or less	50-150
Not suitable	Medium	High	Practically impervious	Sheepsfoot roller, rubber-tired roller	80-110	5 or less	25-100
Not suitable	Slight	Very high	Fair to poor	Compaction not practical	-	-	-

limits; suffix d (e.g., GMd) will be used when the liquid limit is 25 or less and the

thickness of lift are properly controlled. In some instances, several types of equipment
of two types may be necessary.
with limited fines or screenings. Rubber-tired equipment is recommended for softer materials

densities for some materials (based on contact pressure of approximately 65 to 150 psi).
necessary to obtain the required densities for some materials. The area of the feet should

CBR FAMILY OF CURVES ANALYSIS

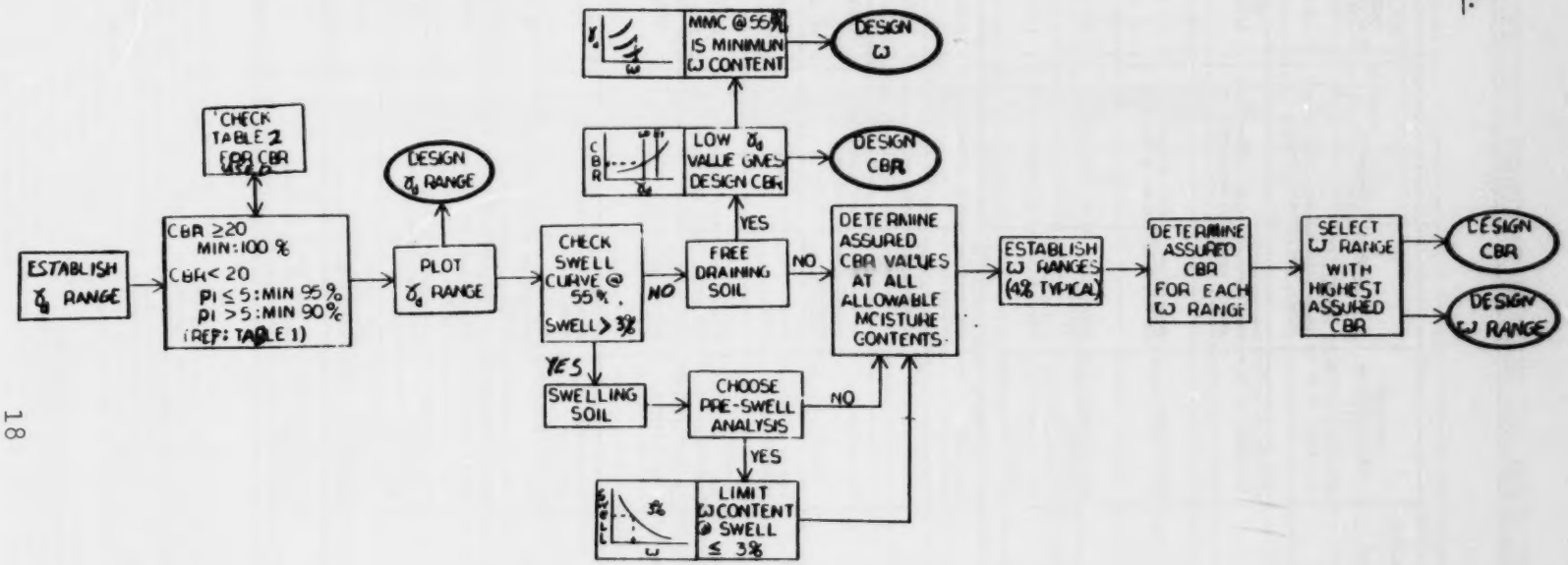


FIGURE 9.

V. NON-SWELLING SOILS

A. Test program.

This test program is applicable to the majority of soils used in construction. As Table 2 indicates, soils which fall into this grouping may be used as compacted subgrade, select, or subbase materials depending on their strengths, quantities, and proximity to the construction site. To illustrate the methodology of evaluating design CBR, the data given on the CBR analysis sheet for "Hope Road" will be used. This data was taken from the subgrade along a proposed road alignment. The object of the following analysis is to determine a soil placement moisture content range for a specified level of compactive effort which gives the greatest assured design CBR. To develop this data, the soils analyst must accomplish the following:

1. Establish the OMC of the soil at 55 blows/layer. This is done using the standard CE55 compaction test. For this example the OMC is 14%.

2. Establish a moisture range for CBR investigation. TM 5-530 states that the range is OMC+4%. This is a time saving guide, as experience has shown that the maximum CBR will normally occur at compaction moisture contents within this range and that testing soils beyond these limits is wasted effort. For this example, the moisture content range of investigation is 10 to 18%.

3. Compact the samples within the moisture content range of investigation at different levels of compactive effort. This is done to allow for evaluation of soil strength when field placement is at something other than 100% of CE55. The levels of compactive effort selected for testing are dependent on the compaction requirements specified in Table 1. If the soil is expected to be used as compacted subgrade or select material with a CBR value of less than 20, it will be placed at less than 100% CE55, and laboratory compactive efforts of 12, 26, and 55 blows/layer are usually selected. If the soil is a very high quality subgrade or a subbase, with a CBR value of 20 or greater, the laboratory tests should include samples compacted in excess of 55 blows per layer. Normally 26, 55, and 72 blows/layer are adequate. The only stipulation placed on the levels of compactive effort to be used is that a 55 blow/layer compaction curve be obtained, and that data is developed at two other levels of compactive effort encompassing the specified field placement densities. In this example, the soil is a CL (cohesive) subgrade so samples were compacted at 12, 26, and 55 blows/layer.

4. Soak samples and measure swell. The initial assumption from Table 2 was that this is a non-swelling soil. It is emphasized that this categorization based upon USCS classification is only an approximation. The swell must be monitored to verify the fact that the tested soil is in fact non-swelling.

5. Perform CBR penetration tests and determine

corrected CBR for each sample. This is done according to the technique previously discussed. Note the fact that accumulation of the required data involves a considerable amount of work. At a minimum, 15 molds (5 per level of compactive effort) must be made. In this example 21 molds were compacted, soaked, and penetrated. The results are given in the "Data Summary".

6. Plot the data on graphs of dry density vs. molding moisture content and corrected CBR vs. molding moisture content.

7. Reformat the data on the CBR family of curves data sheet. This step is taken in order to identify values of dry density and CBR for whole integer moisture contents within the range of investigation at each level of compactive effort. Some of this data may be transferred directly from the data summary table. The remainder must be interpolated from the CBR/dry density vs. molding moisture content graphs.

8. Plot the CBR family of curves. The object of this step is to place the laboratory data in a form which lends itself to analysis. In essence, what is being done is the establishment of trends of strength variation as the moisture content and dry density change. The blank places between actual data points are being filled in. Drawing a CBR family of curves involves considerable practice, numerous attempts, and subsequent adjustments. From the example, it can be seen that the available data has been plotted on a graph of corrected CBR vs. molded dry density for constant moisture contents. Here it can be seen that for low molding water contents (from 10 to 12%) there was an increase in strength with dry density, and at high moisture contents(16 to 18%) the reverse was found to be true. For the intermediate moisture contents, there was an increase in strength to some point, and then a decrease as the dry density increased.

B. Engineering Analysis.

The work done to this point is the job of the laboratory technician. However, it is the responsibility of the engineer to insure that the CBR ata is properly obtained and presented. More importantly, analysis of the data with an understanding of how the results affect the design and impact on economic considerations is the key responsibility of the engineer. Prior to considering the details of the analysis, it is possible to observe two points of interest about the soil being used for the example. First, the maximum strength of this soil does not occur at OMC but at 1.[illegible]% dry of that value(see corrected CBR vs. molding water content). Secondly, from the CBR family of curves, it appears that for some moisture contents, the soil loses strength as the dry density or level of compactive effort increases. The impact of these two factors is important in that if maximum strength from this soil is desired, that strength might be achieved at a moisture content dry of OMC and at some level of compactive effort less than CE55. The reasons for these two phenomena are highly speculative.

For the purposes of this course, it is essential that the engineer realize that soil placement at OMC and the most compactive effort possible are not always the answers to good construction.

1. Establish a density range at which the soil will be placed in the field. Minimum limits for field compaction requirements are based on settlement criteria and are given in Table 1. To facilitate construction, it is normal practice to specify a reasonable range of densities which can be economically obtained and then examine the strength values which would occur within that range. Establishment of the density range depends to a large degree on economics. The greater the latitude given the builder, the better are the chances of the soil being placed within the established limits. However, if an extreme range is stipulated, the CBR value allowed for design might be reduced and thicker pavement structure could be required. Experience has shown that a five percent range(i.e. 90 to 95% of max CE55 dry density) is reasonable. Another factor to consider is actual field compaction experience obtained from either a test strip or prior construction. Such data can be accumulated by measuring the in-place dry densities obtained for different numbers of passes with the available compaction equipment and determining the point where additional passes give little increase in density.

For this example, the soil according to Table 1 must be compacted to at least 90% of max CE55 dry density. It will be assumed that experience with the soil shows that 93% to 98% of max CE55 dry density can be achieved with reasonable effort. This means that the limits of density will be:

$$0.93 \times 130 = 120.9 \text{ pcf}$$

$$0.98 \times 130 = 127.4 \text{ pcf}$$

These limits can be imposed on the CBR family of curves by drawing two vertical lines at 120.9 and 127.4 pcf.

2. Determine the assured CBR values between the specified density limits. If the builder is going to be allowed to place the soil between 120.9 and 127.4 pcf, this step involved determining the CBR values obtained for each moisture content. By observing the change in CBR for any specific moisture content line between the two density limits, it can be seen that a range of strengths is possible. Since the builder will be allowed to place the soil anywhere between the established density limits, the CBR value selected as a potential design strength should represent the worst case. Using 10% moisture as an example, the CBR at 120.9 pcf is 8.5. At 127.4 pcf the CBR is a maximum of 11.3. Of the two, the 8.5 is the minimum strength that can be counted on for the specified density range. This procedure was followed for the remaining moisture contents, and the results are tabulated as follows:

w(moisture)%:	10:	11:	12 :	13 :	14 :	15 :	16:	17:	18:
CBR:	8.5:	9.2:	10.0:	11.3:	13.6:	10.3:	7.4:	5.2:	4.2:

3. Determine the CBR values for potential moisture content specification ranges. As with the density range specified in step 1, a moisture content range which can be economically achieved in the field is desired. Within the overall range of investigation (10 to 14%), a smalles specification range which gives the greatest assured CBR will be determined. Experience has shown that a four percent range(i.e. a value ±2%) is a reasonable requirement; however, this particular span is not intended to represent an absolute rule. The engineer may elect to specify a smaller range to achieve a larger design CBR and a reduction in pavement thickness requirements, but this savings in pavement materials may be offset by increased costs associated with difficulties in meeting the more stringent requirements. Conversely, for some soils an expanded moisture content specification may have little effect on the design CBR. For the example problem a four percent specification range will be considered. One possible range is 10 to 14%. If the engineer specified that the soil be placed within these limits, the worst possible strength that could be realized is a CBR of 8.5(see tabulation under step 2). Such an analysis can be done for the other possible four percent ranges, and the results are as follows:

w% range	10-14	11-15	12-16	13-17	14-18
assured CBR:	8.5	9.2	7.4	5.4	4.2

4. Select the moisture content range which gives the greatest design CBR. In steps 2 and 3, CBR values were selected based on the premise that the engineer is going to allow the builder to place the soil anywhere between potential moisture content and density specification limits. Now it is time for the engineer to select the set of limits he desires. From the tabulation in step 3, it can be seen that the soil will give the largest CBR values when placed between 11 and 15% moisture content. Thus 9.2 becomes the design CBR,and the field quality control measures to be used to insure that a CBR of 9.2 is achieved are:

a. Compact at 93 to 98% of max CE55 dry density (120.9 to 127.4 pcf).
b. Ensure that moisture content is between 11% and 15%.

C. Summary. This technique for determining a design CBR provides for a strength measure of at least 9.2 when the associated density and moisture content ranges are adhered to. Of course, greater strengths might be realized within the specified limits, but the value obtained allows the

engineer to size the structure for the worst conditions within the specifications. Note that for this soil and the size of the limits used, the greatest assured strength did not occur for the four percent moisture content range centered on the OMC. This is a phenomenon that has been found to occur for many soils which have appreciable clay contents. Also of importance is the fact that the analysis was based on an initial selection of density limits. The engineer may find it advantageous to evaluate other density limits that meet the minimums given in Table 1 to see if an adjustment to these limits would yield greater strength.

VI. SWELLING OR EXPANSIVE SOILS

A. General information. There is a small group of soils which can display the characteristic of an objectionable volumetric expansion after being compacted and subjected to subsequent saturation. This presents a problem in pavement design as this expansion or swell can damage the structure by means of a "reverse-settlement" mechanism. The measure of swell used by the Corps of Engineers is termed the "free-swell index" which is expressed as a percentage of the initial sample height. Objectionable swell is defined as that in excess of three percent. The reason for this expansive nature relates primarily to the types of clay minerals present. Montmorillonitic clay, which is just one of several kinds, apperrs to be comprised of the smallest and most highly charged particles found in nature. The combination of large surface area per unit of volume and an equally tremendous ability to expand or shrink as water is taken in or removed from the soil.

Experience has shown that plasticity index is an excellent indicator of expansive soils. The following guidelines have been suggested:

PI	SWELL POTENTIAL
0-14	not expansive
14-25	marginal
25-40	critical
40&up	highly critical

Although a high PI does not guarantee that the soil is expansive, critical soils should be checked more closely for swell tendencies.

B. Engineering Alternatives

CBR ANALYSIS SHEET

(Non-swelling soil)

PROJECT HOPE ROAD

SOIL CLASSIFICATION CL

LOCATION OF SOIL STA 4+00

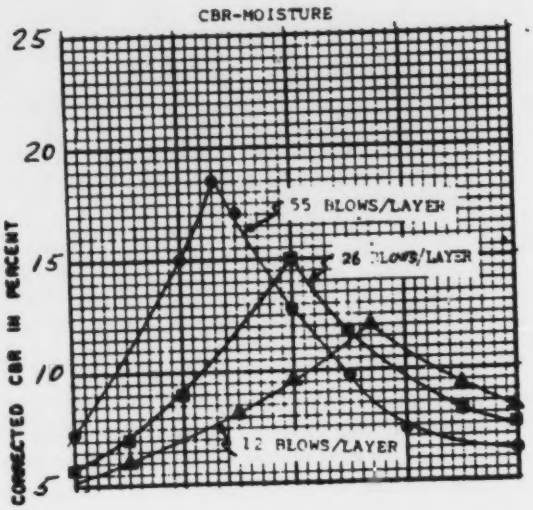
DATE OF TESTS 31 JUNE 1984

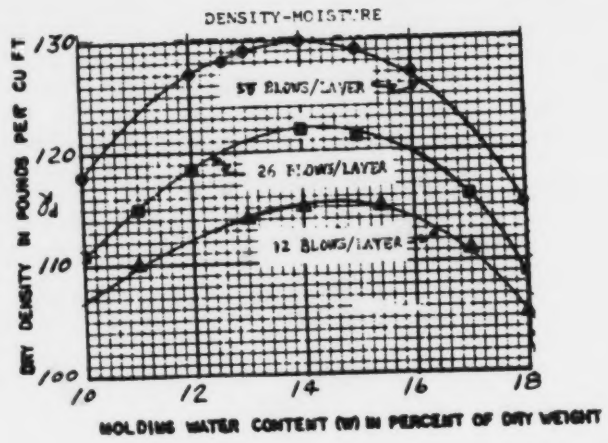
GROUP # N/A

NAME SP/4 WALKER, PFC DRILLOCK

DATA SUMMARY

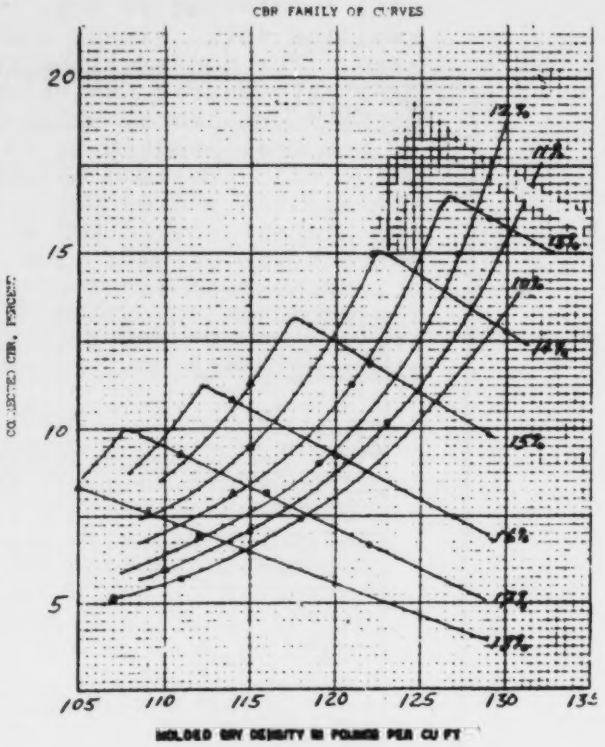
MOLD #	BLOWS PER LAYER	MOISTURE CONTENT w %	DRY DENSITY γ_d	CORRECTED CBR %
1	12	11	110	6.0
2		13	114	8.2
3		14	115	9.5
4		15.4	115	12.0
5		17	111	9.3
6		18	105	8.3
7	26	10	111	5.7
8		11	115	7.0
9		12	118.5	9.0
10		14	122	15.0
11		15	121.5	11.9
12		17	116	8.2
13		18	109	7.6
14	55	10	118	7.4
15		12	127	15.0
16		12.6	128	18.5
17		13	129	17.0
18		14	130	12.8
19		15	129	9.8
20		16	127	7.4
21		18	115	6.4





CBR FAMILY OF CURVES DATA SHEET

(W%)		12 BLOWS/LAYER	26 BLOWS/LAYER	55 BLOWS/LAYER
10	γ_d	107 LBS/FT³	111 LBS/FT³	118 LBS/FT³
	C_{BR}	5.2 %	5.7 %	7.4 %
11	γ_d	110 LBS/FT³	115 LBS/FT³	123 LBS/FT³
	C_{BR}	6.0 %	7.0 %	10.2 %
12	γ_d	112 LBS/FT³	119 LBS/FT³	127 LBS/FT³
	C_{BR}	7.0 %	9.0 %	15.0 %
13	γ_d	114 LBS/FT³	121 LBS/FT³	129 LBS/FT³
	C_{BR}	8.2 %	11.5 %	17.0 %
14	γ_d	115 LBS/FT³	122 LBS/FT³	130 LBS/FT³
	C_{BR}	9.5 %	15.0 %	12.8 %
15	γ_d	115 LBS/FT³	122 LBS/FT³	129 LBS/FT³
	C_{BR}	11.3 %	11.8 %	9.8 %
16	γ_d	114 LBS/FT³	120 LBS/FT³	127 LBS/FT³
	C_{BR}	10.8 %	9.2 %	7.4 %
17	γ_d	111 LBS/FT³	116 LBS/FT³	122 LBS/FT³
	C_{BR}	9.3 %	8.2 %	6.7 %
18	γ_d	105 LBS/FT³	109 LBS/FT³	115 LBS/FT³
	C_{BR}	8.3 %	7.6 %	6.4 %



DESIGN CBR

COMPACTION RANGE: _____ % TO _____ %
_____ LBS/FT³ TO _____ LBS/FT³

W%	LOWEST CBR	W% RANGE	ASSURED CBR
		% TO %	
		% TO %	
		% TO %	
		% TO %	
		% TO %	
		% TO %	
		% TO %	
		% TO %	
		% TO %	

DESIGN CBR (HIGHEST ASSURED) _____

DESIGN MOISTURE RANGE _____% TO _____%

C. Test Program.

Table 2 indicates that the potentially expansive soils by USCS classifiation are the CHs, MHs, and OHs. The test procedure for determination of a design CBR for an expansive soil is similar to that previously discussed for the non-swelling soil, except that the objective is not exactly the same. For non-swelling soils, the object was to find the greatest assured CBR value for some range of densities and moisture contents, while for expansive soils the objective of the test program is to find the moisture content ranges which will preclude objectionable swell and also provide the highest soaked CBR. Generally, the minimum swell and the highest soaked CBR will occur at a molding moisture content wet of OMC. The following is an example of such a test program for a CH soil taken from the subgrade at the proposed "Airfield Delta". As the majority of the steps are similar to those developed for the case of non-swelling soils, only differences will be discussed.

1. Establish the OMC of the soil at 55 blows/layer.

2. Establish a moisture range for CBR investigation. The OMC$\pm$4% range of investigation may not apply. It may be necessary to prepare samples over a wider range of moistures with the majority of the work being done on samples wet of OMC. In the example, samples were prepared over a range of OMC$\pm$8%, and it will be illustrated later that much of the laboratory work done on samples dry of OMC is not essential.

3. Compact samples within the moisture content range of investigation at different levels of compactive effort. As the type of soil being tested will be cohesive and have a CBR below 20, Table 1 indicates that compaction must be no less than 90% of max CE55 dry density. An upper limit can be established by reason of practicality as expansive soils are very difficult to compact at levels greater than 100% of max CE55 dry density. Therefore, laboratory compactive efforts of 12, 26, and 55 blows/layer are adequate for nearly all cases.

4. Soak samples and measure swell. This step is a major deviation from the equivalent for the non-swelling case. For each sample, the expansion is measured, the percent swell is computed, and the percent swell is plotted against the molding water content. As an example the triangular data point at 10% moisture on the attached "swell data curve" was obtained as follows:

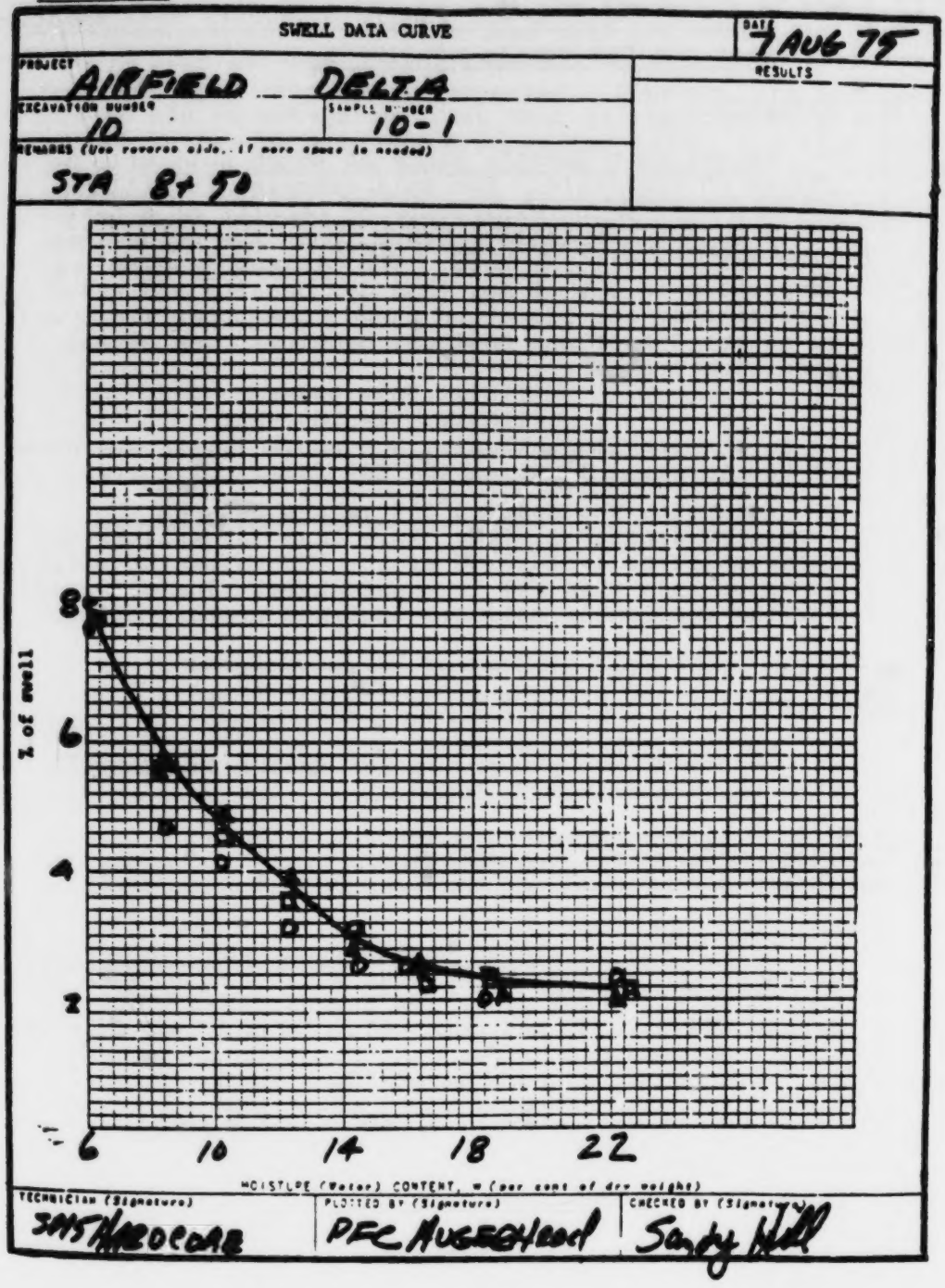
Initial sample height: 4.50 inches
Height after soaking: 4.72 inches
Molding water content: 10.0%
Level of compactive effort = blows/layer
Free swell index = percentage of swell =

$$\frac{4.72 - 4.50}{4.50} \times 100 = 4.9\%$$

After obtaining the swell index for each mold to be penetrated, these points are plotted on a swell vs. molding moisture content graph. A curve is then fit (usually to only the CE55 data points), an example of

which is shown in Figure 10. From this particular curve, it can be ascertained that only soil placed at molding moisture contents of 14% or greater will swell 3% or less.

FIGURE 10.



5. Perform CBR penetration tests and determine the corrected CBR for each sample.

6. Plot the data on graphs of dry density vs. molding moisture content and corrected CBR vs. molding moisture content.

7. Reformat data on CBR family of curves data sheet.

8. Plot the CBR family of curves.

D. Analysis.

1. Establish a density range at which soil will be placed in the field. For this example, it will be assumed that prior experience or benefit of a test strip is not available. Hence, only the guidelines from Table 1 will be used. The minimum level of compaction is 90% of max CE55 dry density and assuming a reasonable specification gange, the upper limit will be set at 95% of max CE55 dry density. The actual densities are:

$(110)x(.90)= 99pcf$
$(110)x(.95)= 104.5pcf$

As in the previous example, the above limits are shown by two vertical lines on the CBR family of curves.

2. Determine the assured CBR values between the specified density limits. More than 3% swell is not acceptable, so evaluation of the CBR values at moisture contents less than 14% is unnecessary. The CBR values for the applicable moisture contents are as follows:

w%	14	15	16	17	18	19	20
CBR	3.4	4.2	3.2	2.2	1.3	0.9	0.4

3. Determine the CBR values for potential moisture content specification ranges.

w% range	14-18	15-19	16-20
CBR	1.3	0.9	0.4

4. Select the moisture content range which gives the greatest design CBR. From step 3, it can be seen that the 14 to 18% range gives the largest CBR. Thus the design CBR is 1.3, and this value is obtained when the soil is placed at:

$w = 14$ to 18%
$\gamma_d = 99$ to 104.5 pcf

E. Summary. The first thing the engineer must consider if he encounters an expansive soil is going somewhere else to build the structure. However, this is not always feasible, and this technique does allow for determination of a design CBR at which swell is not excessive. It is emphasized that obtaining this design value was done at the expense of strength. This technique does not provide for the event of the soil being dried to a moisture content less than the amount at placement. Should such extreme drying take place, excessive shrinkage and pavement failure might be expected. However, the engineer has to his advantage the fact that it takes considerable effort to remove water from expansive soils, and that such soils will normally be protected from drying by the overlying pavement. Another alternative to building on expansive soils is chemical stabilization. Fortunately, addition of small amounts of lime reduces considerably the potential for shrinkage and swell.

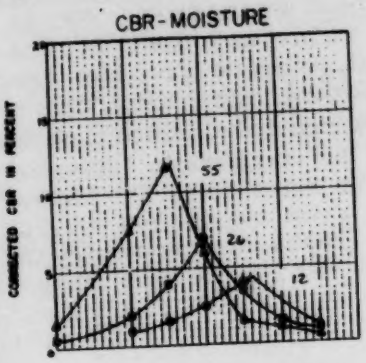
CBR ANALYSIS SHEET

PROJECT: Airfield Delta
SOIL CLASSIFICATION: CH
LOCATION OF SOIL: Borrow Pit #5
DATE OF TESTS: 7 Aug 75
GROUP #: NA
NAME: SPS Handcock, PFC Auerbach

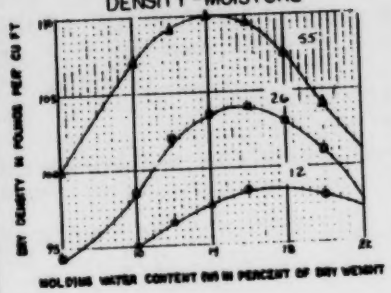
DATA SUMMARY

MOLD NO.	BLOWS PER LAYER	MOISTURE CONTENT w %	DRY DENSITY γ_d	CORRECTED CBR %
1	12	10.0	95.0	1.0
2		12.0	96.5	1.5
3		14.0	97.5	2.5
4		16.0	98.5	4.0
5		20.0	98.0	1.2
6	26	6.0	94.0	0.5
7		10.0	98.5	2.0
8		12.0	102.0	4.0
9		14.0	103.5	7.0
10		16.0	104.0	3.5
11		18.0	103.0	1.5
12		20.0	101.0	1.0
13	55	6.0	100.0	1.5
14		10.0	102.0	7.5
15		12.0	109.0	11.5
16		14.0	110.0	6.0
17		16.0	109.5	1.5
18		18.0	107.5	1.0
19		20.0	104.0	0.5

CBR - MOISTURE



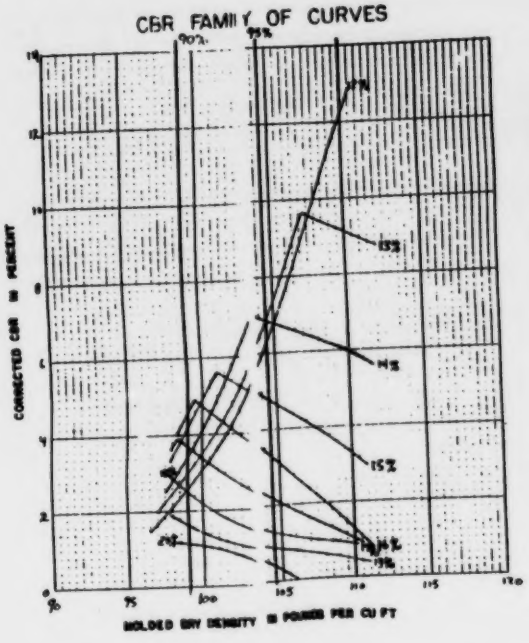
DENSITY - MOISTURE



CBR FAMILY OF CURVES DATA

(w%)		12 BLOWS/LAYER	26 BLOWS/LAYER	55 BLOWS/LAYER
12	γ_d	96.5 LBS/FT³	102.0 LBS/FT³	109.3 LBS/FT³
	CBR	1.5 %	4.0 %	11.5 %
13	γ_d	97.1 LBS/FT³	102.8 LBS/FT³	109.7 LBS/FT³
	CBR	2.0 %	5.4 %	9.2 %
14	γ_d	97.6 LBS/FT³	103.5 LBS/FT³	110.0 LBS/FT³
	CBR	2.5 %	7.0 %	6.0 %
15	γ_d	98.1 LBS/FT³	103.9 LBS/FT³	109.8 LBS/FT³
	CBR	3.3 %	4.9 %	3.4 %
16	γ_d	98.4 LBS/FT³	104.0 LBS/FT³	109.5 LBS/FT³
	CBR	4.0 %	3.5 %	1.5 %
17	γ_d	98.6 LBS/FT³	103.7 LBS/FT³	108.8 LBS/FT³
	CBR	3.8 %	2.4 %	1.3 %
18	γ_d	98.5 LBS/FT³	103.0 LBS/FT³	107.5 LBS/FT³
	CBR	2.7 %	1.5 %	1.0 %
19	γ_d	98.4 LBS/FT³	102.0 LBS/FT³	105.8 LBS/FT³
	CBR	1.8 %	1.1 %	0.8 %
20	γ_d	98.0 LBS/FT³	101.0 LBS/FT³	104.0 LBS/FT³
	CBR	1.2 %	1.0 %	0.5 %

CBR FAMILY OF CURVES



DESIGN CBR

CORRECTION RANGE: ____ % to ____ % ____ Lbs/Ft³ to ____ Lbs/Ft³

WC	LOWEST CBR	WC RANGE	ASSURED CBR
		% to %	
		% to %	
		% to %	
		% to %	
		% to %	
		% to %	
		% to %	
		% to %	
		% to %	

DESIGN CBR (HIGHEST ASSURED): ____ ____

DESIGN MOISTURE RANGE: ____ % to ____ %

pages tightly bound

VII. FREE-DRAINING SOILS

A. Test program. Determination of a design CBR for this group of soils requires the least testing of the three remolded laboratory test programs. Table 2 gives the USCS classification and the uses of the soils that fall into this group. The ease in testing is due to the free-draining characteristics or lack of fines in the soil. From the CBR analysis sheet for borrow pit "A", it can be seen that the density vs. moisture content curves have a concave upward shape and show maximum densities between 7 and 9% moisture depending on the level of compactive effort. For each curve, there is a limiting moisture content(shown by the triangle, diamond, or circle) at which moisture above that required to fill the voids after compaction is squeezed or drained from the soil. The dashed lines to the right of the limiting moisture content represent attempts to compact the soil in a saturated condition but the result after conpaction is densities and moisture contents at the limiting condition. This means that for such soils, field placement is relatively easy. To insure maximum dry density,for any level of compactive effort, the only control measure that must be accomplished is to have more water available than that required for the maximum dry density at the appropriate level of compactive effort. From the corrected CBR vs. molding water content curves, it can be seen that the same pattern exists in relation to moisture content as to the dry density. Soils placed wet of the limiting moisture content achieve the maximum CBR possible for that level of compactive effort. In other words, moisture contents of loose soils above the limiting values have little bearing on the strength of a soil after compaction. This makes laboratory testing, field placement, and field control a relatively easy matter. To illustrate what must be done to arrive at a design CBR, the steps as outlined in the previous examples will again be followed.

1. Establish the OMC of the soil at 55 blows/layer. The OMC for this example is the limiting moisture content or 8%. To insure that a free-draining soil is being tested, this curve should display a maximum dry density at a limiting moisture content.

2. Compact samples at different levels of compactive effort. Compaction curves must be made for three levels of compactive effort up to the limiting moisture contents. As these soils frequently have CBR values greater than 20, the placement compactive effort is in excess of 100% of max CE55 dry density. Therefore, 26, 55, and 72 blows/layer are usually used.

3. Soak samples amd measure swell. Swell measurements are not required and soaking can be eliminated when it is determined that saturation does not affect the strength.

4. Perform CBR penetration tests. Only the samples at the limiting moisture contents for each level of compactive effort need be tested. Normally more than one sample at the limiting conditions will be made for each level of compactive effort and all should be tested.

5. Plot the data on graphs of dry density vs. molding moisture content and corrected CBR vs. moldiig moisture content. Only the plot of dry density vs. molding water content is required. The corrected CBR vs. molding water content graph is presented only for discussion.

6. Plot the CBR family of curves. This graph can be condensed into a single line. The three data points are obtained by plotting the corrected CBR against the associated dry density at the limiting moisture content.

7. Establish a density range at which the soil will be placed in the field. Using the criteria from Table 1 and noting that the CBR for this soil is always greater than 20, the minimum level of compaction allowed is 100% of max CE55 dry density. As there is a lack of additional information, specify 100 to 105% of max CE55 dry density. This means compaction between 120 pcf and 126 pcf.

8. Determine the design CBR and placement moisture content. From the family of curves, it can be seen that the minimum CBR is 70 at 120 pcf. The placement moisture content necessary to insure that this strength is obtained is 8% or greater.

B. Summary. It can be seen that considerably greater CBR values can be achieved if more field compaction is applied to the soil. If this is not too costly, it may be advantageous to specify greater densities. Lastly, it must be emphasized that the short cuts used in this procedure are dependent upon the fact that the soil is actually free-draining. This can be determined from the shapes of the compaction curves.

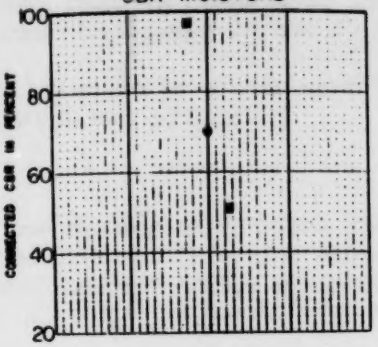
CBR ANALYSIS SHEET

PROJECT: AIRFIELD BOLD EAGLE
SOIL CLASSIFICATION: GW
LOCATION OF SOIL: STA 3+50
DATE OF TESTS: 1 MAY 84
GROUP:
NAME: SP5 D.P. SPORKE

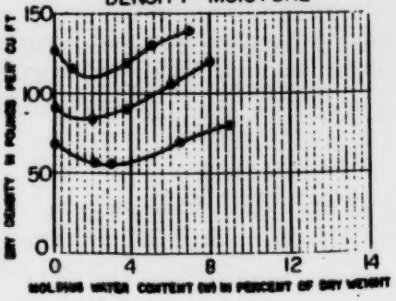
DATA SUMMARY

MOLD NO.	BLOWS PER LAYER	SOAKING MOISTURE CONTENT %	DRY DENSITY pcf	CORRECTED CBR %
1	26	0	68.0	
2		2.1	56.3	
3		3.0	55.9	
4		6.5	69.1	
5		9.0	80.0	51
6	55	0	90.1	
7		2.0	84.9	
8		3.8	90.0	
9		6.0	106.1	
10		8.0	120.0	70
11	72	0	126.0	
12		1.9	115.1	
13		3.8	119.3	
14		5.1	131.9	
15		7.0	139.1	97

CBR - MOISTURE



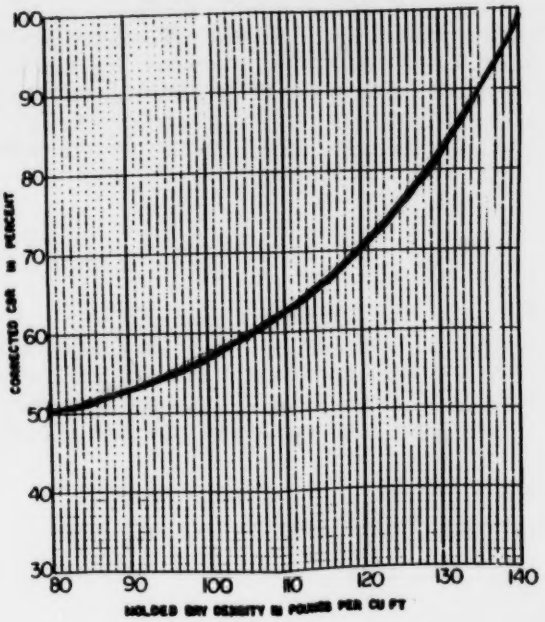
DENSITY - MOISTURE



CBR FAMILY OF CURVES DATA

(w)(%)		BLOWS/LAYER	BLOWS/LAYER	BLOWS/LAYER
	γ_d	80 LBS/FT³	LBS/FT³	LBS/FT³
	CORR C_{BR}	51 %	%	%
	γ_d	LBS/FT³	120 LBS/FT³	LBS/FT³
	CORR C_{BR}	%	70 %	%
	γ_d	LBS/FT³	LBS/FT³	139.1 LBS/FT³
	CORR C_{BR}	%	%	97 %
	γ_d	LBS/FT³	LBS/FT³	LBS/FT³
	CORR C_{BR}	%	%	%
	γ_d	LBS/FT³	LBS/FT³	LBS/FT³
	CORR C_{BR}	%	%	%
	γ_d	LBS/FT³	LBS/FT³	LBS/FT³
	CORR C_{BR}	%	%	%
	γ_d	LBS/FT³	LBS/FT³	LBS/FT³
	CORR C_{BR}	%	%	%
	γ_d	LBS/FT³	LBS/FT³	LBS/FT³
	CORR C_{BR}	%	%	%

CBR FAMILY OF CURVES



DESIGN CBR

COMPACTION RANGE: ____ % to ____ % (____ LBS/FT³ to ____ LBS/FT³)

W%	LOWEST CBR	W% RANGE	ASSIGNED CBR
		% to %	
		% to %	
		% to %	
		% to %	
		% to %	
		% to %	
		% to %	
		% to %	
		% to %	
		% to %	

DESIGN CBR (LOWEST ASSIGNED): ____

DESIGN MOISTURE RANGE: ____ % to ____ %

STUDENT NOTES

PRACTICAL EXERCISES

California Bearing Ratio

#1. Using the data from the "Hope Road" project, answer the following questions. (SEE pages 24 and 25 for data)

a. What will the CBR be if the soil is placed at 15% moisture content and 135 pcf?

b. If you use the design CBR from the class exercise to determine the pavement thickness above the compacted subgrade, what happens to the pavement performance when the soil is placed as in question"a" above?

c. How are your answers changed if you stipulate a 3% moisture range (OMC ± 1½%) for the same density ranges used in the class problem?

d. What is the design CBR for densities of 90 to 95 per cent of the maximum CE55 dry density and a 4% moisture content specification range?

#2. You had your soils analyst perform a complete CBR analysis of the subgrade found along a proposed road alignment. You were furnished with the following data including a complete CBR family of curves. Determine the design CBR and best moisture content if this soil is placed between 92% and 96% of maximum CE55 dry density. Plot the specification block on the CE 55 compaction curve. (SEE Figures 11 and 12 on page 38)

#3. Use the swell and CBR analysis data sheets for the Karlsruhe Airfield, on pages 39 thru 41 , to determine the design CBR of the soil for the conditions stated in questions "a" through "e", and answer questions "f" through "h". NOTE: Samples were compacted at 12, 26, and 55 blows per layer.

a. The density range is 90% to 95% of max CE55 dry density and the four percent moisture range gives the highest CBR with 3% or less swell.

b. The density range is 90% to 95% of max CE55 dry density and the 3% moisture content range gives the highest CBR with 3% or less swell.

c. The density range is 91% to 96% of the max CE55 dry density and the 4% moisture content range that gives the highest CBR with 3% or less swell.

d. The density range is 91% to 96% of max CE55 dry density and the 3% moisture content range that gives the highest CBR with 3% or less swell.

e. The density range is 90% to 95% of the max CE55 dry density and the 4% moisture content range that gives the highest CBR. Consider all moisture contents given on the CBR family of curves.

f. From the results of situations "a" and "c", how does increasing the compaction affect the design strength of the soil?

g. How is the design strength of the soil affected by including swell in the analysis? EXPLAIN.

h. Do you consider the amount of data(i.e. the ranges of moisture content and levels of compactive effort) to be adequate for determination of a design CBR? EXPLAIN.

CBR

#4. Use the data from "Mason's Pit" (SEE Figures14 and15) to answer the following questions.

a. Does this soil have the properties that allow it to be tested and analyzed as a free-draining soil? How can you tell?

b. What is the design CBR of the soil for 102% to 107% of maximum CE55 dry density?

c. What placement moisture content would you specify to achieve the design CBR?

d. What is the minimum level of compactive effort required by Corps specifications and why is this limit imposed?

FIGURE 11.

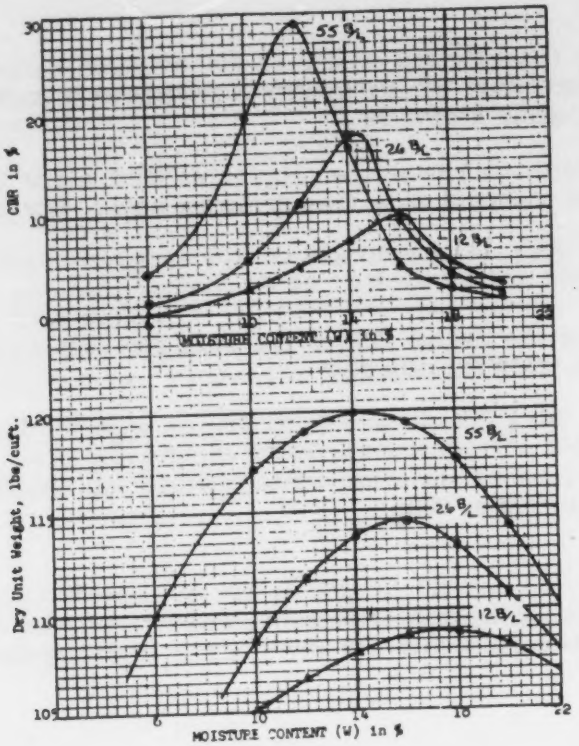


FIGURE 12.

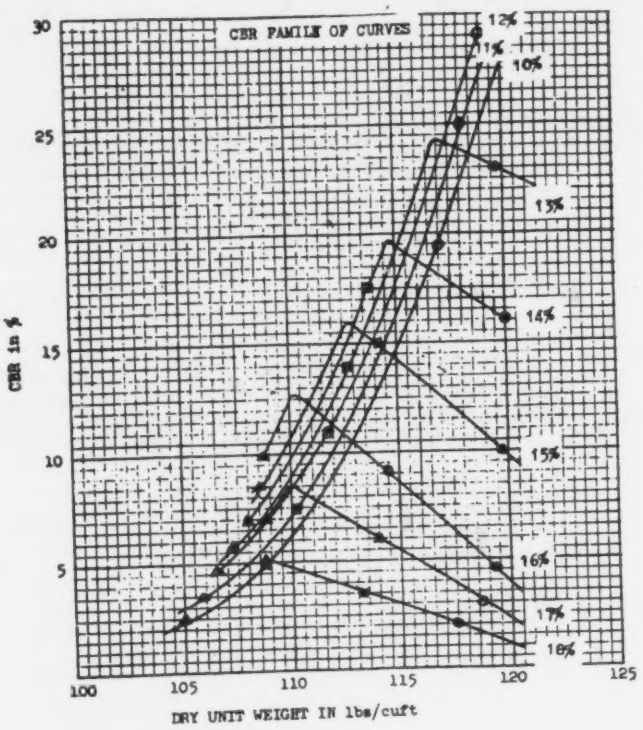
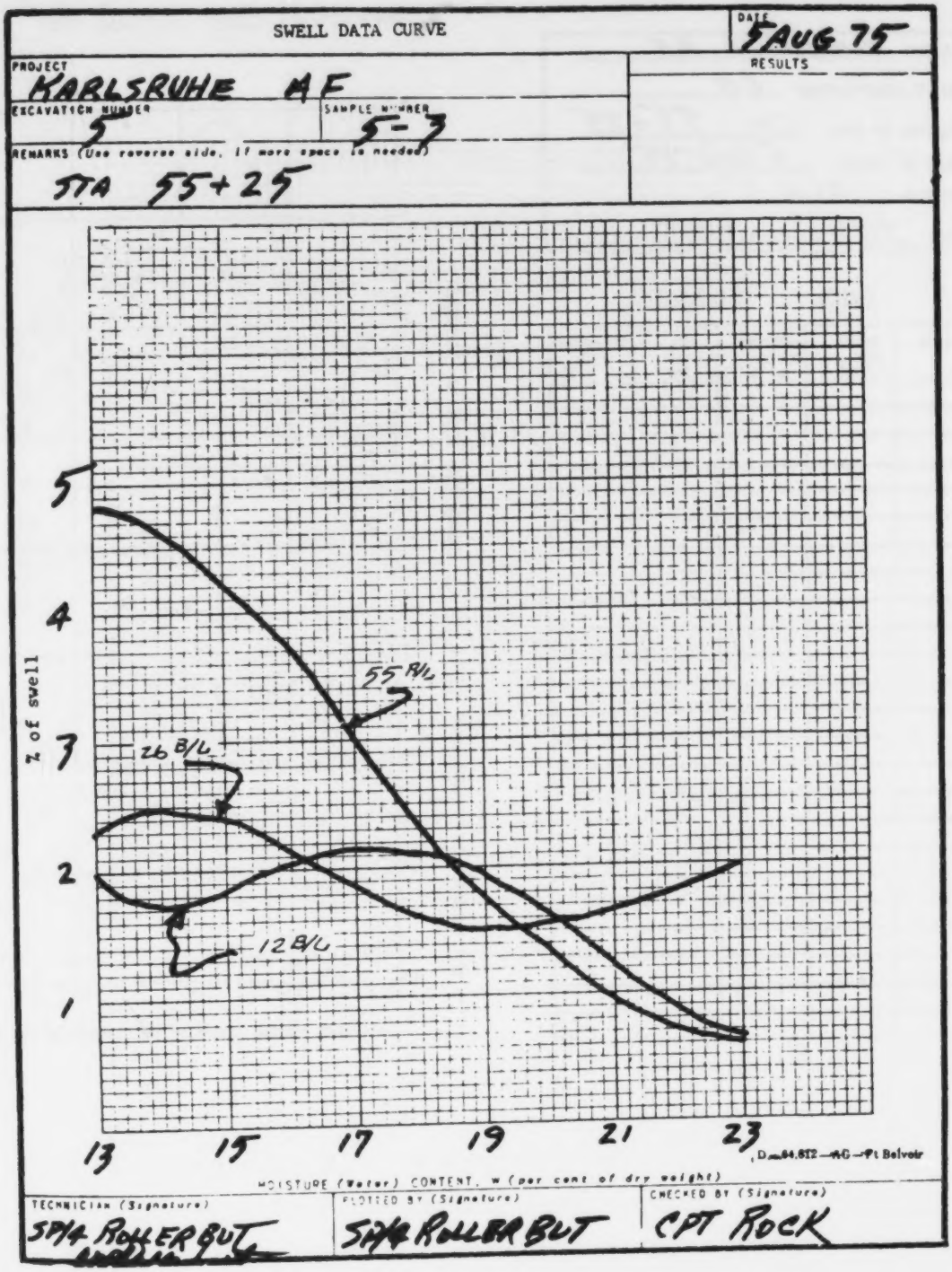


FIGURE 13.


SWELL DATA CURVE
DATE 5 AUG 75
PROJECT KARLSRUHE AF
RESULTS
EXCAVATION NUMBER 5
SAMPLE NUMBER 5-3
REMARKS (Use reverse side, if more space is needed)
STA 55+25
% of swell
5
4
3
2
1
55 B/L
26 B/L
12 B/L
13
15
17
19
21
23
MOISTURE (Water) CONTENT, w (per cent of dry weight)
TECHNICIAN (Signature)
SP/4 ROLLER BUT
PLOTTED BY (Signature)
SP/4 ROLLER BUT
CHECKED BY (Signature)
CPT ROCK

CBR ANALYSIS SHEET

PROJECT KARLSRUHE AE

SOIL CLASSIFICATION CH

LOCATION OF SOIL STA 55+25

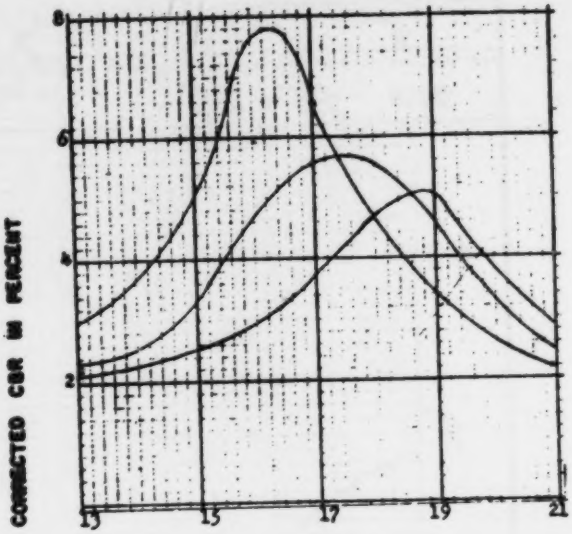
DATE OF TESTS 5 AUG 75

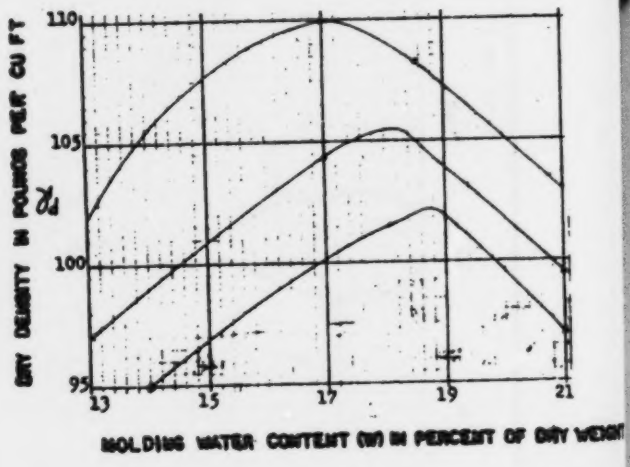
GROUP #: N/A

NAME SP4-ROLLER BUT

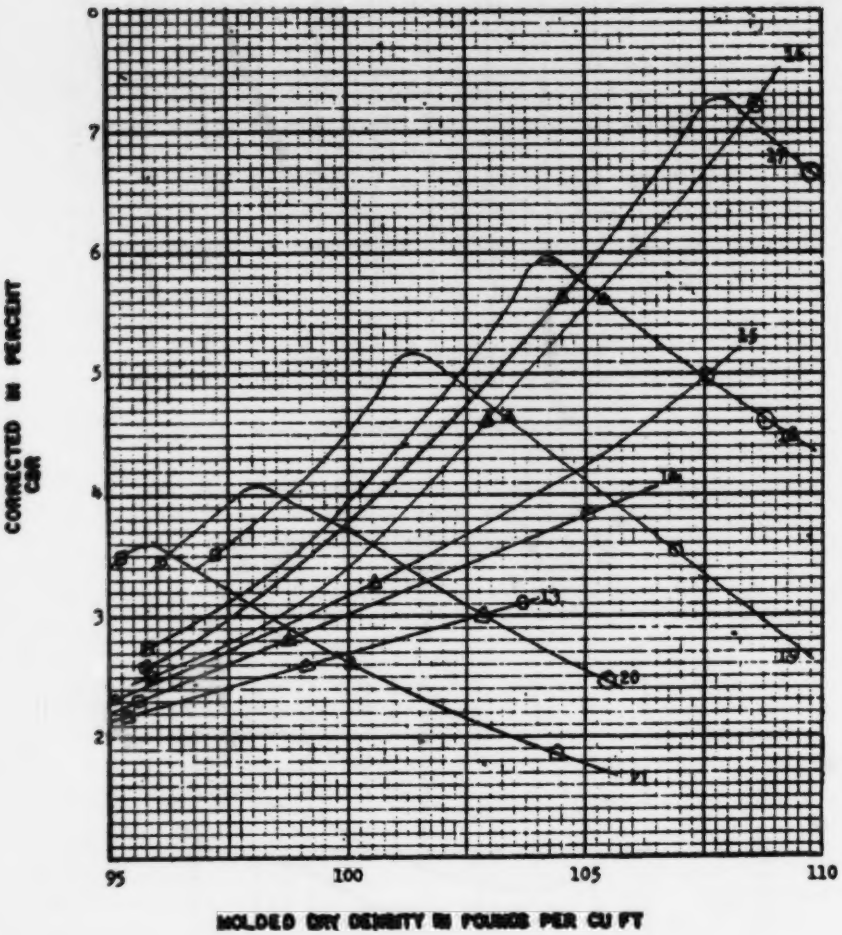
DATA SUMMARY

MOLD #	BLOWS PER LAYER	MOISTURE CONTENT w %	DRY DENSITY γ_d	CORRECTED CBR %





CBR ANALYSIS SHEET (continued)



Mason's Pit (SP)

FIGURE 14.

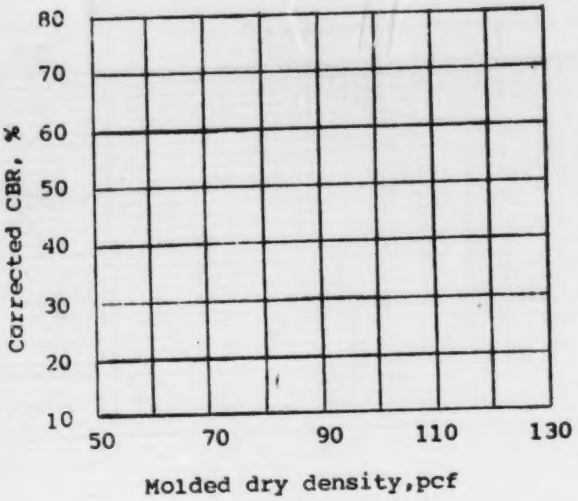
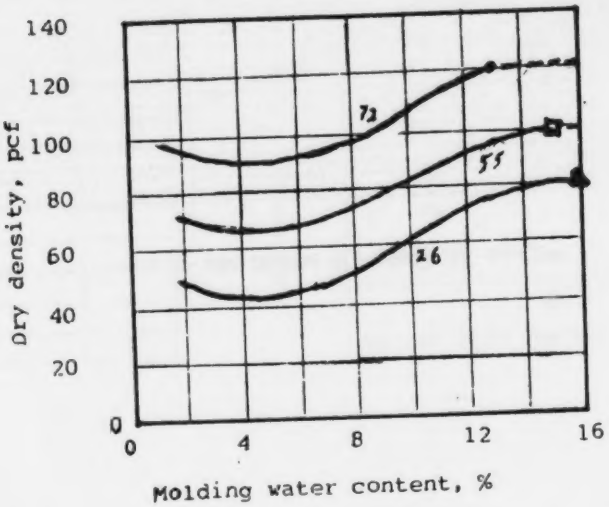


FIGURE 15.

At limiting moisture contents		
γ_d, pcf	w, %	CBR, %
120	13	60
100	15	40
80	16	30



SOILS STABILIZATION

I. INTRODUCTION

A. Objectives: Using given soil test data, the student will be able to determine if stabilization is necessary, and if it is required, he will be able to determine the most efficient method, the amount of stabilization materials required, and the construction sequence required for that particular method.

B. Soil stabilization is defined as any process that improves the engineering properties of a soil. It differs from soil modification in that stabilization must increase the strength of the soil. It is usually a process of blending or mixing materials with the soil to increase the soil's strength and durability.

II. OBJECTIVES OF SOIL STABILIZATION

A. Increase the soil strength -

B. Reduce susceptibility to frost -

C. Control swelling and shrinking -

D. Improve the workability of the soil -

E. Control the amount of water entering or moving through the soil(waterproofing) -

F. Dust control -

G. Permit the use of thinner pavements -

III. SOIL QUALITY INDICATORS

Quality indicators can be used to identify certain undesireable properties in soils which make the soils unsuitable for use in construction. By identifying these soils the engineer can make informed decisions as to what remedial action should be taken.

A. Test procedures

1. Identify the soil using the USCS or the field ID card

2. Determine the gradation - it indicates susceptibility to frost activity and/or deterioration.

3. Determine the density and moisture content.

4. Determine the CBR - it indicates the shear strength of the soil.

5. Find the Atterberg limits - the LL is an indicator of workability and the susceptibility to ground-water pumping.

6. Calculate the PI - it indicates swell potential and workability. See Table 5 .

B. If the soil is found to be unsuitable, the engineer must determine what corrective measures should be taken.

IV. CORRECTIVE MEASURES

A. Place the soil properly at dry density and moisture content specifications.

B. Design to fit the situation(use thicker pavement or better materials).

C. Go somewhere else to build - avoid trouble.

D. Stabilize. Because of the cost in time and resources, stabilization should be used only when absolutely necessary.

1. When it is determined that stabilization is required, more tests, either deliberate or expedient, are needed to determine:

a. the type of stabilizer needed(see Fig.20 or Table 21).

b. the amount of stabilizer required.

c. the best moisture content and density for the compacted soil.

Refer to TM 5-530 for specific test procedures.

2. Time required for tests(see Table 4).

Because time is so precious in tactical situations, the need for rapid completion of a project may over-ride the requirement for a complete test series.

TABLE 4. ESTIMATED TIME REQUIRED FOR TEST PROCEDURES

TYPE OF CONSTRUCTION	STABILIZING AGENT	TIME REQUIRED FOR TEST*
Expedient/Tactical	Lime	None
	Cement	None
	Bitumen	1 hour
Non-expedient/ deliberate	Lime	7 days
	Cement	6 to 9 days
	Bitumen	1 day

* These criteria do not include time required for gradation and classification tests on the untreated soil.

TABLE 5 . Expedient PI identification

PLASTICITY DESCRIPTION	PLASTICITY INDEX RANGE	REACTION TO CRUSHING BETWEEN FINGERS
NON-PLASTIC	0 to 3	falls apart easily
SLIGHTLY PLASTIC	4 to 8	is easily crushed
MEDIUM PLASTIC	9 to 30	difficult to crush
HIGHLY PLASTIC	31 or more	impossible to crush

V. METHODS OF STABILIZATION

A. Mechanical Stabilization- is the process of mixing or blending soils of two or more gradations to obtain a material meeting the required specifications. The soil blending may take place at the construction site, at a central plant, or at a borrow area. The blended material is then spread and compacted conventionally, as required.

1. For subbase and select material requirements SEE Table 7-1, TM 5-330, page 7-9.

2. For base course requirements SEE Table 7-3, TM 5-330, page 7-12.

3. For surface course requirements SEE Tables10-6 and10-7, TM 5-330, pages 10-25 and 10-26.

B. Admixture Stabilization - is the addition of a chemically active cementing agent or a bituminous material to the soil.

1. Chemical stabilizers

a. Portland cement - can be used to modify and improve the quality of a soil or to transform the soil into a cemented mass, which significantly increases its strength and durability. The amount of cement added will depend on whether the soil is to be modified or stabilized.

b. Lime - can improve the quality of a soil by changing some of the physical properties or can increase the strength and durability of the soil by transforming it into a stabilized mass. Either hydrated lime or quick-lime may be used.

c. Lime-cement-fly ash(LCF) - can be used to stabilize coarse grained materials which contain little or no fines, to give them high compressive strengths. The lime and fly ash react to form a cement-like material, and the Portland cement fraction is included to accelerate and increase the reaction and strength gained.

d. Others -

2. Bituminous materials - are often used to seal a soil against penetration by water or to hold a loose soil in place. Asphalt cutbacks, cements, and emulsions are all used.

C. Fabrics and Geotextiles - are various types of materials used to distribute loads over larger areas to increase the bearing capacity of soils, or used as barriers to control soil and soil moisture movement.

1. Types of materials	Pro	Con
a. MO-MAT		
b. Sand grid		
c. Geotextiles		
d. Others		

2. Construction equipment.

   a. Transportation

   b. Placement

   c. Surfacing

3. Construction techniques.

4. Principles involved, and materials which exhibit those principles.

Material names

   a. load distribution -

   b. separation -

   c. filtration -

   d. drainage -

   e. reinforcement -

D. Field Expedients - are temporary methods used when the time or resources for true stabilization are not available.

   1. Chespalling -

   2. Sand blanket -

   3. Army track -

   4. Corduroy road -

   5. Others - the most severely limiting factor is the limit of one's imagination.

VI. STABILIZATION METHODS IN DETAIL

A. Requirements for mechanical stabilization.

1. See Tables 6 through 8 following and TM 5-330 for the specific requirements for each course.

2. The addition of an available type of soil material to the existing soil at the site must create a condition that satisfies the requirements on the appropriate table(s).

TM 5-330 gives gradation and plasticity requirements for the various structural layers as outlined below:

SUBBASE AND SELECT MATERIAL REQUIREMENTS

Table 7-1. Recommended Maximum Permissible Values of Gradation and Atterberg Limit Requirements in Subbases and Select Materials

TABLE 6.

Material	Maximum design CBR		Size inches		Gradation requirements % passing				Atterberg limits			
					No. 10		No. 200		LL		PI	
	Airfields	Roads	Airfields	Roads	Airfields	Roads	Airfields	Roads	Airfields	Roads	Airfields	Roads
Subbase	50	50	3	2	50	50	15	15	25	25	5	5
Subbase	40	40	3	2	80	80	15	15	25	25	5	5
Subbase	30	30	3	2	100	100	15	15	25	25	5	5
Select Material	Below 20	20	3	3	.....	.....	25	.....	35	35	12	12

BASE COURSE REQUIREMENTS

Table 7-3. Desirable Gradation for Crushed Rock, Gravel, or Slag, and Uncrushed Sand and Gravel Aggregates for Base Courses

TABLE 7.

Sieve designation	Percent passing each sieve (square openings) by weight				
	Maximum aggregate size				
	3-inch	2-inch	1½-inch	1-inch	1-inch sand-clay
3-inch	100				
2-inch	65–100	100			
1½-inch	.....	70–100	100		
1-inch	45–75	55–85	75–100	100	100
¾-inch	.....	50–80	60–90	70–100	
⅜-inch	30–60	30–60	45–75	50–80	
No. 4	25–50	20–50	30–60	35–65	
No. 10	20–40	15–40	20–50	20–50	65–90
No. 40	10–25	5–25	10–30	15–30	33–70
No. 200	3–10	0–10	5–15	5–15	8–25

Less than 15% passing No. 200
LL less than 25
PI less than 5

For emergency and minimum operational airfields:

LL less than 45
PI less than 15 with good drainage provided.

SURFACE COURSE REQUIREMENTS

Table 10-6. Suggested Grading Requirements f Gravel and Composite Type Surface Courses o Processed Materials

TABLE 8.

Sieve designation	*Perce passing by wei*
1-inch	10
¾-inch	85–10
⅜-inch	65–10
No. 4	55–8
No. 10	40–7
No. 40	25–4
No. 200	10–2

LL less than 35
PI between 4 and 9

NOTE: A proportioning technique chart m be used to determine how much of each type of material should be mixed to give the required final gradation.

SAMPLE PRACTICAL EXERCISE

We have available two materials with gradations as below:

Sieve Sizes[1]	Glacial Till (GP)[2]	CL[3]
1 inch	100	100
3/4 inch	85	100
3/8 inch	53	100
#4	21	100
#10	99	96
#40	0	71
#200	0	52

The stabilized material will be used as a base course material (minus 1"). Determine the final gradation of the mix.

4. See TM5-330, Table 7-3.
5. Is the mean of the spec range.
6. $A=\frac{\Sigma B}{\Sigma A+\Sigma B}$; 7. $B=\frac{\Sigma A}{\Sigma A+\Sigma B}$

SIEVE SIZE 1	PERCENT PASSING				$\lvert\bar{S}-A\rvert$ (5-1)	$\lvert\bar{S}-B\rvert$ (5-2)	____A 6	____B 7	PERCENT PASSING, FINAL MIX (6+7)
	SOIL A 2	SOIL B 3	SPEC'S S 4	$\bar{S}$ 5					
					$\Sigma_A=$	Σ_B			

B. Admixture stabilization in detail

1. Stabilization with portland cement.

a. Portland cement can be used to modify and improve the quality of the soil or to transform the soil into a cemented mass, either of which significantly increases its strength and durability. The amount of cement additive will depend on whether the soil is to be modified or stabilized. The only limitation to the amount of cement to be used to stabilize or modify a soil pertains to the treatment of the base courses to be used in flexible pavement systems. When a cement-treated base course is to be surfaced with asphaltic concrete, the percent of cement by weight will be limited to 4% for Air Force pavements.

b. Cement content for modification of soils.

(1) The amount of cement required to improve the quality of the soil through modification is determined by the trial-and-error approach. If it is desired to reduce the PI of the soil, successive samples of soil-cement mixtures must be prepared at different treatment levels and the PI of each mixture must be determined. The minimum cement content that yields the desired PI is selected, but since it was determined based on the #40(-) fraction of the material, this value must be adjusted to find the design cement content based on total sample weight expressed as:

$$A = 100(B)(C)$$

where A=design cement content as a % of total weight, B= %passing a #40 sieve, expressed as a decimal, and C= %cement required to obtain the desired PI in the #40(-) material, expressed as a decimal.

(2) If the objective of modification is to improv the gradation of granular soil through the additic of fines, the analysis should be conducted on samples at various treatment levels to determine the minimum acceptable cement content. The determination of cement content to reduce the swell potential of fine-grained plastic soils can be accomplished by molding several samples at various cement contents and soaking the specimens for 4 days. The lowest cement content that eliminates the swell potential or reduces the swel characteristics to the minimum becomes the design cement content. The cement content determined to accomplish soil modification should be checked to see whether it provides an unconfined compressive strength great enough to qualify for a reduced thickness design in accordance with the criteria established for soil stabilization in Tables 9 an

(3) Cement-modified soil also may be used in frost areas, but in addition to the procedures for mixture design described in (1) and (2) above, cured specimens should be subjected to the 12 freeze-thaw cycles test (omitting wire brushing) or other applicable freeze-thaw procedures, followed by frost susceptibility tests to ensure that it meets the requirements for the base course. If the cement-modified soil is used as the subgrade, its frost susceptibility, determined after freeze-thaw cycling, should be used as the basis of the pavement thickness design if the reduced subgrade strength design method is applied.

c. Cement content for cement-stabilized soil.

The following procedure is recommended for determining the design cement content for cement-stabilized soils.

(1) Step 1. Determine the classification and gradation of the untreated soil. The soil must meet the gradation requirements shown in Table 12 before it can be used in a reduced thickness design.

(2) Step 2. Select an estimated cement content from Table 11 using the soil classification.

(3) Step 3. Using the estimated cement content, establish a compaction curve and determine the maximum dry density for the soil-cement mixture.

(4) Step 4. Using the untreated soil gradation characteristics, cement content, and maximum dry density determined in steps1, 2, and 3, respectively, verify the estimated cement content using Table 13 or 14 and Figure 16 depending on the soil classification. If the estimated cement content from Step 2 varies by more than ±2% from the value in Table 13 or 14, coduct additional compaction tests, varying the cement content, until the value from Table 13 or 14 is within ±2% of that used for the moisture density test.

(5) Step 5. Prepare samples of the soil-cement mixture for unconfined compression and durability tests at the dry density and at the cement content determined in Step 4 and at cement contents 2% above and 2% below that determined in Step 4. The samples should be prepared in accordance with TM 5-530, except that when more than 35% of the material is retained on the #4 sieve a CBR mold should be used to prepare the specimens. Cure the specimens for 7 days in a humid room before testing. Test three subspecimens using the unconfined compression test, and subject three specimens to durability tests, either wet-dry tests for pavements located in non-frost areas or freeze-thaw tests for pavements located in frost areas.

(6) Step 6. Compare the results of the unconfined compressive strength and durability tests with the requirements shown in Tables 9 and 10. The lowest cement content which has the required unconfined compressive strength and demonstrates the required durability is the design cement content. If the mixture meets the durability

Table 9. Minimum Unconfined Compressive Strengths for Cement, Lime, and Combined Lime-Cement-Fly Ash Stabilized Soils

Stabilized Soil Layer	Minimum Unconfined Compressive Strength, psi[a]	
	Flexible Pavement	Rigid Pavement
	Air Force and Army	All
Base course	750	500
Subbase course, select material or subgrade	250	200

[a] Unconfined compressive strength determined at 7 days for cement stabilization and 28 days for lime or lime-cement-fly ash stabilization.

Table 10. Durability Requirements

Type of Soil Stabilized[a]	Maximum Allowable Weight Loss After 12 Wet-Dry or Freeze-Thaw Cycles Percent of Initial Specimen Weight
	Army and Air Force
Granular, PI < 10	11
Granular, PI > 10	8
Silt	8
Clays	6

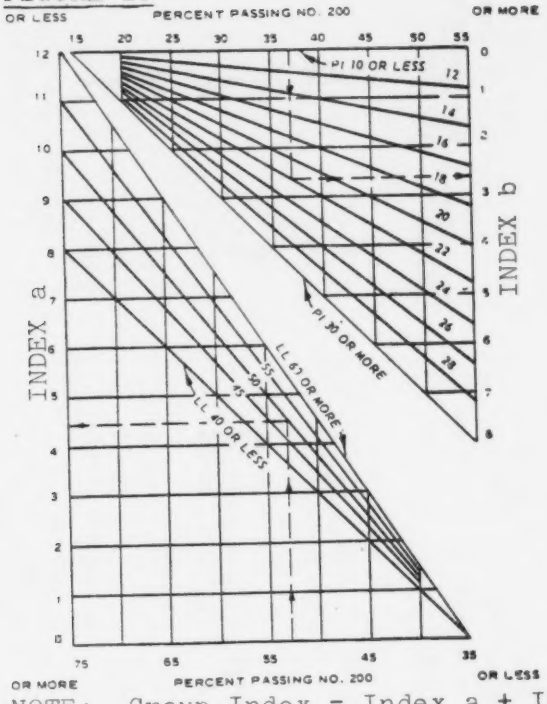
Table 11. Estimated Cement Requirements for Various Soil Types

Soil Classification	Initial Estimated Cement Requirement Percent Dry Weight
GW-SW	5
GP, SW-SM, SW-SC, SW-GM, SW-GC	6
GM, SM, GC, SC, SP-SM, SP-SC, GP-GM, GP-GC, SM-SC, GM-GC	7
SP, CL, ML, ML-CL	10
MH, OH	11
CH	10

Table 12. Gradation Requirements for cement-stabilized soils.

Type Course	Sieve Size	Percent Passing Army and Air Force
Base	2-in.	100
	1-1/2-in.	70-100
	1-in.	45-100
	3/4-in.	--
	1/2-in.	30-90
	No. 4	20-70
	No. 10	15-60
	No. 30	--
	No. 40	5-40
	No. 200	0-20
Subbase	3-in.	100
	No. 4	--
	No. 10	--
	No. 100	--
	No. 200	0-25

FIGURE 16



NOTE: Group Index = Index a + Index b.

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Table 13. Average Cement Requirements for Granular and Sandy Soils

Material Retained on No. 4 Sieve percent	Material Smaller Than 0.05 mm percent	Cement Content, Percent by Weight Maximum Dry Density, lb/cu ft (Treated Material) 116-120	121-126	127-131	132-137	138-142	143 or more
0-14	0-19	10	9	8	7	6	5
	20-39	9	8	7	7	5	5
	40-50	11	10	9	8	6	5
15-29	0-19	10	9	8	6	5	5
	20-39	9	8	7	6	6	5
	40-50	12	10	9	8	7	6
30-45	0-19	10	8	7	6	5	5
	20-39	11	9	8	7	6	5
	40-50	12	11	10	9	8	6

Note: Base course goes to 70 percent retained on the No. 4 sieve.

Table 14. Average Cement Requirements for Silty and Clayey Soils

Group* Index	Material Between 0.05 and 0.005 mm percent	Cement Content, Percent by Weight Maximum Dry Density, lb/cu ft (Treated Material)						
		99-104	105-109	110-115	116-120	121-126	127-131	132 or more
0-3	0-19	12	11	10	8	8	7	7
	20-39	12	11	10	9	8	8	7
	40-59	13	12	11	9	9	8	8
	60 or more	--	--	--	--	--	--	--
3-7	0-19	13	12	11	9	8	7	7
	20-39	13	12	11	10	9	8	8
	40-59	14	13	12	10	10	9	8
	60 or more	15	14	12	11	10	9	9
7-11	0-19	14	13	11	10	9	8	8
	20-39	15	14	11	10	9	9	9
	40-59	16	14	12	11	10	10	9
	60 or more	17	15	13	11	10	10	10
11-15	0-19	15	14	13	12	11	9	9
	20-39	16	15	13	12	11	10	10
	40-59	17	16	14	12	12	11	10
	60 or more	18	16	14	13	12	11	11
15-20	0-19	17	16	14	13	12	11	10
	20-39	18	17	15	14	13	11	11
	40-59	19	18	15	14	14	12	12
	60 or more	20	19	16	15	14	13	12

*From Figure 16.

requirements but not the strength requirements, the mixture is considered to be a modified soil.

2 STABILIZATION WITH LIME

a. Lime can be used either to modify some of the physical properties and thereby improve the quality of a soil or to transform the soil into a stabilized mass, which increases its strength and durability. The amount of lime additive will depend upon whether the soil is to be modified or stabilized. The lime to be used may be either hydrated or quicklime, although the preponderance of stabilization is accomplished using hydrated lime, since quicklime is highly caustic and dangerous to use. The design lime contents determined from the criteria presented herein are for hydrated lime. As a guide, the lime contents determined herein for hydrated lime should be reduced by 25 percent to determine a design content for quicklime.

b. Lime content for lime-modified soils. The amount of lime required to improve the quality of a soil is determined through the same trial-and-error process used for cement-modified soils (para 1b).

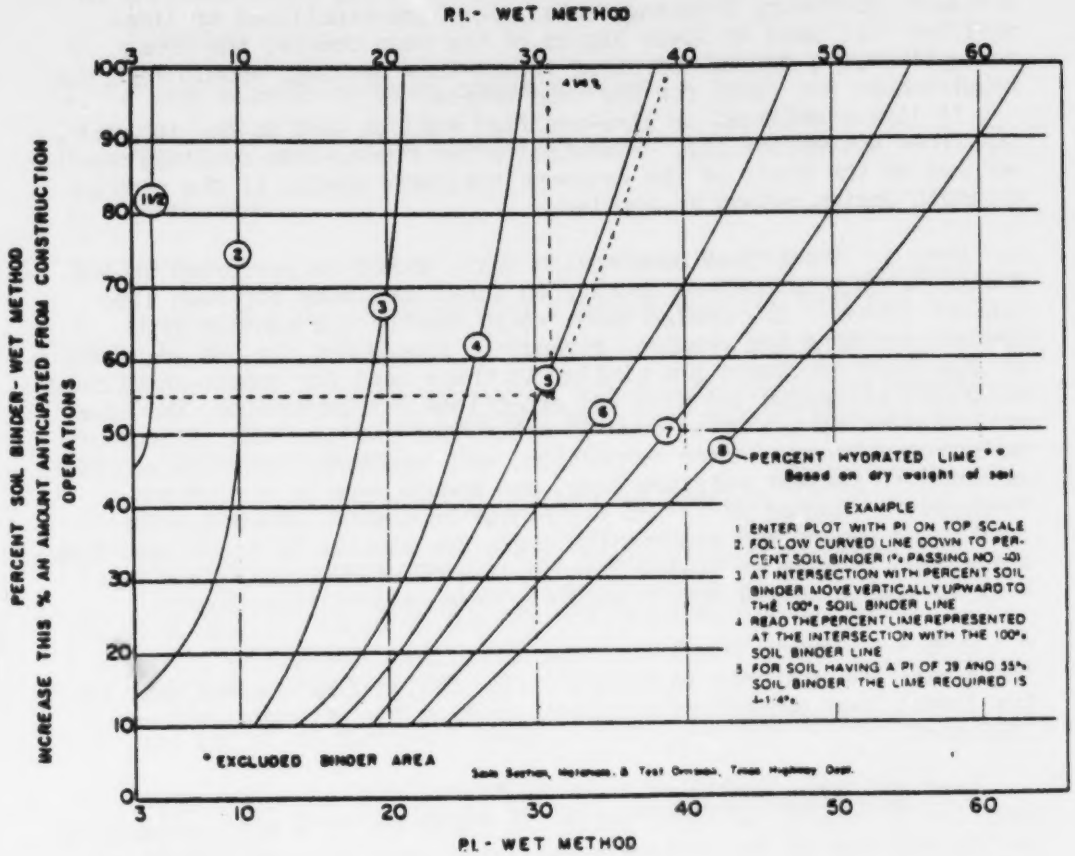
c. Lime content for lime-stabilized soils.

(1) Strength requirements. To take advantage of the thickness reduction criteria, the lime-stabilized soil must meet the unconfined compressive strengths shown in table 9 as well as the durability requirements in table 10.

(2) Procedures. When lime is added to a soil, a combination of reactions begins to take place immediately and is nearly complete within an hour, although substantial strength gain is not reflected for some time. These reactions result in a change in both the chemical composition and physical properties. Most lime, when placed in a water solution, has a pH of about 12.4. Therefore, the pH is a good indicator of the desirable lime content of a soil-lime mixture. The reaction that takes place when lime is introduced to a soil generally causes a significant change in the plasticity of the soil; therefore, the changes in the plastic and liquid limits also become an indicator of the desired lime content. Two methods are presented for determination of the initial design lime content.

(a) Step 1. The preferred method is to prepare several mixtures at different lime treatment levels and determine the the pH of each mixture after 1 hour. The lowest lime content producing the highest pH of the soil-lime mixture is the initial design lime content. Procedures for conducting a pH test on lime-soil mixtures are presented at the end of this section. In frost areas, specimens must be subjected to the freeze-thaw test as discussed in step 2 below. An alternate method of determining an initial design lime content is by the use of figure 17. Specific values required to use figure 17 are the PI and the percent of material passing the No. 40 sieve. These properties are determined from plastic limit and gradation tests on the untreated soil.

FIGURE 17.



* Exclude use of chart for materials with less than 10% - No. 40 and cohesionless materials (PI less than 3)

** Percent of relatively pure lime usually 90% or more of Ca and/or Mg hydroxides and 85% or more of which pass the No. 200 sieve. Percentages shown are for stabilizing subgrades and base courses where lasting effects are desired. Satisfactory temporary results are sometimes obtained by the use of as little as 1/2 of above percentages. Reference to cementing strength is implied when such terms as "Lasting Effects" and "Temporary Results" are used.

(Courtesy of the National Lime Association, Washington, D.C.)

b. Step 2. After the initial lime content has been estimated, conduct a compaction test with the lime-soil mixture following the same procedures for soil-cement except that the mixture should be allowed to cure no less than 1 hour and no more than 2 hours in a sealed container before molding. Compaction will be accomplished in 5 layers using 55 blows of a 10-pound hammer having an 18-inch drop. The moisture-density should be determined at lime contents equal to design +2% and +4% for the preferred method and at design ±2% for the alternate method. In frost areas, cured specimens should be subjected to the 12 freeze-thaw cycles(OMIT wire brushing) or other applicable freeze-thaw procedures, followed by frost susceptibility determinations in standard laboratory freezing tests. For lime-stabilized or lime-modified soil used in lower layers of the base course, the frost susceptibility, determined after freeze-thaw cycling, should meet the requirements set forth for the base course.

If lime-stabilized or lime-modified soil is used as the subgrade, its frost susceptibility, determined after freeze-thaw cycling, should be used as the basis of the pavement thickness design if the reduced strength design method is applied.

c. Step 3. Unconfined compression tests should be performed at the design percent of maximum density on three specimens for each lime content tested. The design value would then be the minimum lime content yielding the required strength. Procedures for the preparation of lime-soil specimens are similar to those used for cement-stabilized soils(SEE paragraph 1c) with two exceptions. After mixing, the lime-soil mixture should be allowed to mellow for not less than 1 hour or more than 2 hours; after compaction, each specimen should be wrapped securely to prevent moisture loss, and should cure in a constant temperature chamber at 73° F. ± 2°F. for 28 days. Procedures for conducting unconfined compression tests are similar to those used for soil-cement specimens except that in lieu of moist curing, the lime-soil specimens should remain securely wrapped until testing.

d. Step 4. Compare results of the unconfined compressive strength tests with the criteria in Table 9. The design lime content must be the lowest lime content of specimens meeting the strength criteria indicated.

C. Lime and other additives. If lime is used as a preliminary additive to reduce the PI or alter the gradation of a soil preparatory to the addition of the primary stabilizing agent such as bitumen or cement, then the design lime content is the minimum treatment level that will achieve the desired results. For non-plastic and low-PI materials in which lime alone generally is not satisfactory for stabilization, the addition of fly ash may be needed to produce the necessary reaction.

pH TEST TO DETERMINE LIME REQUIREMENTS FOR LIME STABILIZATION

1. Materials: Lime(to be used for soil stabilization).

2. Equipment:

   a. pH meter(must have an electrode with a pH range of 14).

   b. Plastic bottles (150 ml minimum capacity) with screw-top lids.

   c. Plastic beakers (50 ml)

   d. Distilled water.

   e. A beam balance or other accurate scale.

   f. Oven.

   g. Water cans.

3. Procedure

   a. Standardize the pH meter with a buffer solution that has a pH of 12.45.

   b. Weigh representative samples of air-dried soil to the nearest 0.01 gram. They must all pass the #40 sieve and be equal to 20.0 grams of oven-dried soil.

   c. Pour the soil samples into the 150 ml bottles.

   d. Add varying percentages of lime, weighed to the nearest 0.01 gram, to the soils. (Lime percentages of 0, 2, 3, 4, 5, 6, 8, and 10, based on the dry soil weight, may be used.)

   e. Thoroughly mix soil and dry lime.

   f. Add 100 ml of distilled water to the soil-lime mixtures.

   g. Shake the soil-lime and water for a minimum of 30 seconds or until there is no evidence of dry material on the bottom of the bottle.

   h. Shake the bottles for 30 seconds every 10 minutes.

   i. After 1 hour, transfer part of the slurry to a plastic beaker and measure the pH.

   j. Record the pH for each of the soil-lime mixtures. The lowest % of lime which gives a pH of 12.40 is the % required to stabilize the soil. If the pH does not reach 12.40, the minimum lime content which gives the highest pH is used to stabilize the soil.

3. STABILIZATION WITH LIME-CEMENT-FLYASH (LCF)

Stabilization of coarse-grained soils having little or no fines can often be accomplished by the use of the LCF combination. Fly ash is a pozzolanic material, consisting mainly of silicon and aluminum coumpounds that, when mixed with lime and water, forms a hardened cementitious mass capable of obtaining high compressive strengths. Thus, lime and fly ash in combination can often be used successfully in stabilizing granular materials having few fines since the fly ash provides an agent with which the lime can react. In addition to lime and fly ash, a small amount of portland cement is also added to accelerate and increase strength gain. The use of LCF mixtures is not permitted for Air Force Airfield pavements, if the cement content exceeds 4 percent.

a. Suitable materials. Types of materials suitable for the LCF stabilization are coarse-grained soils having no more than 12 percent of the material passing the No. 200 sieve. In addition, the PI of the minus 40 fraction should not exceed 25.

b. Initial mix proportion will be 1% portland cement, 4% lime, 24% fly ash, and 71% soil. Minimum unconfined compressive strength requirements are indicated in table 9. If test specimens do not meet strength requirements, add cement in increments of ½ percent until strengths are adequate. The total quantity of additives should not exceed 15 percent by weight. In frost areas, the LCF mixture should meet the weight loss criteria specified for cement-stabilized soils. The specimens should be compacted in CBR mold.

4. STABILIZATION WITH BITUMEN

a. Types of bituminous-stabilized soils.

(1) Soil-bitumen - is a cohesive soil system made water-resistant with a bituminous mixture.

(2) Sand-bitumen - is a system in which sand is cemented together by bituminous material.

(3) Oiled earth - is an earth-road system made resistant to water absorption and abrasion by means of a sprayed application of slow-cure or medium-cure liquid asphalts.

(4) Bitumen-waterproofed, Mechanically stabilized soil - is a system in which 2 or more soil materials are blended to produce a good gradation of particles from coarse to fine, relatively small amounts of bitumen are needed, and the processed soil is compacted.

(5) Bitumen-lime blend - is a system in which small percentages of lime are blended with fine grained soils to facilitate the penetration and mixing of bitumens into the soil.

b. Soil gradation. The recommended soil gradations for subgrade materials and base or subbase courses are shown in Tables 15 and 17, respectively. Mechanical stabilization may be required to bring the soil to the proper gradation.

c. Types of bitumen. Bituminous stabilization is usually done using asphalt cement, asphalt cutback, or asphalt emulsions. The type of bitumen used depends on the type of soil to be stabilized, the method of construction, and the weather conditions. In frost areas, the use of tar as a binder should be avoided because of its reactions to extreme temperatures. Asphalts are affected less by temperature changes, but a grade of asphalt suitable to the prevailing climate should be selected. As a general rule, the most satisfactory results are obtained when the most viscuous liquid asphalt that can be readily mixed into the soil is used. For higher quality mixes in which a central plant is used, viscosity-grade asphalt cements should be used. Much bituminous stabilization is done in place with the bitumen being applied directly to the soil or soil-aggregate system and the mixing and compaction operations being conducted immediately thereafter. For this type of construction, liquid asphalts, i.e. cutbacks and emulsions, are used. Emulsions are preferred over cutbacks because of energy constraints and pollution control efforts. The specific type and grade of bitumen will depend on the characteristics of the aggregate, the type of construction equipment, and the climatic conditions. Generally, the following types of bituminous materials will be used for the soil gradations indicated in Table 16.

d. Mix design. Guidance for the design of bituminous-stabilized base and subbase courses is contained in TM 5-822-8, Chapter 9. For subgrade stabilization, the following equation may be used for estimating the preliminary amount of asphalt cutback to be used:

$$p = \frac{0.02(a) + 0.07(b) + 0.15(c) + 0.20(d)}{(100 - S)} \times 100$$

where:

p = the % asphalt cutback by weight of dry aggregate.

a = the % of mineral aggregate retained on the #50 sieve.

b = the % of aggregate retained on the #100 sieve but passing the #50 sieve.

c = the % of aggregate passing the #100 sieve but retained on the #200 sieve.

d = the % of aggregate passing the #200 sieve.

S = the % solvent

The preliminary amount of emulsified asphalt to be used in stabilizing subgrades can be determined from Table 12. Figures (18a) and (18b) can be used to find mix design for asphalt cement. The final design content of asphalt should be selected based on the results of the Marshall* Stability test procedure. The minimum Marshall Stability recommended for subgrades is 500 pounds. If a soil does not show increased stability when reasonable amounts of bituminous materials are added, the gradation of the soil should be modified or another type of bituminous material should be used. Poorly graded materials may be improved by the addition of suitable fines containing a considerable amount of material that passes the #200 sieve. The amount of bitumen required for a given soil increases with an increased percentage of finer sized material.

Table 15. Recommended Gradations for Bituminous-Stabilized Subgrade Materials

Sieve Size	Percent Passing
3 in.	100
No. 4	50-100
No. 30	38-100
No. 200	2-30

*For a detailed explanation of the Marshall Stability Test, refer to TM 5-530, pp. 3-26 through 3-38.

TABLE 16. AGGREGATE / BITUMINOUS MATERIAL COMBINATIONS.

1. OPEN-GRADED AGGREGATE.

   A. Rapid-cure and medium-cure liquid asphalts(RC-250, RC-800, and MC-3000).
   B. Medium-setting asphalt emulsions(MS-2 and CMS-2).

2. WELL-GRADED AGGREGATE WITH LITTLE OR NO SUB-#200 MATERIAL.

   A. Rapid-cure and medium-cure liquid asphalts(RC-250, RC-800, MC-250, and MC-800).
   B. Slow-curing liquid asphalts(SC-250 and SC-800).
   C. Medium-setting and slow-setting asphalt emulsions(MS-2, CMS-2, SS-1, and CSS-1).

3. AGGREGATE WITH A CONSIDERABLE PERCENTAGE OF SUB-#200 MATERIAL.

   A. Medium-curing liquid asphalts(MC-250 and MC-800).
   B. Slow-curing liquid asphalts(SC-250 and SC-800).
   C. Slow-setting asphalt emulsions(SS-1, SS-1h, CSS-1, and CSS-1h).
   D. Medium-setting asphalt emulsions(MS-2 and CMS-2).

The simplest type of bituminous stabilization is the application of liquid asphalt to the surface of an unbound aggregate road. For this type of operation, the slow-curing and medium curing liquid asphalts(SC-70, SC-250, and MC-250) are used.

Table 17. Recommended Gradations for Bituminous-Stabilized Base and Subbase Materials

Sieve Size	1-1/2-in. Maximum	1-in. Maximum	3/4-in. Maximum	1/2-in. Maximum
1-1/2-in.	100	--	--	--
1-in.	84 ± 9	100	--	--
3/4-in.	76 ± 9	83 ± 9	100	--
1/2-in.	66 ± 9	73 ± 9	82 ± 9	100
3/8-in.	59 ± 9	64 ± 9	72 ± 9	83 ± 9
No. 4	45 ± 9	48 ± 9	54 ± 9	62 ± 9
No. 8	35 ± 9	37 ± 9	41 ± 9	47 ± 9
No. 16	27 ± 9	28 ± 9	32 ± 9	36 ± 9
No. 30	20 ± 9	21 ± 9	24 ± 9	28 ± 9
No. 50	14 ± 7	16 ± 7	17 ± 7	20 ± 7
No. 100	9 ± 5	11 ± 5	12 ± 5	14 ± 5
No. 200	5 ± 2	5 ± 2	5 ± 2	5 ± 2

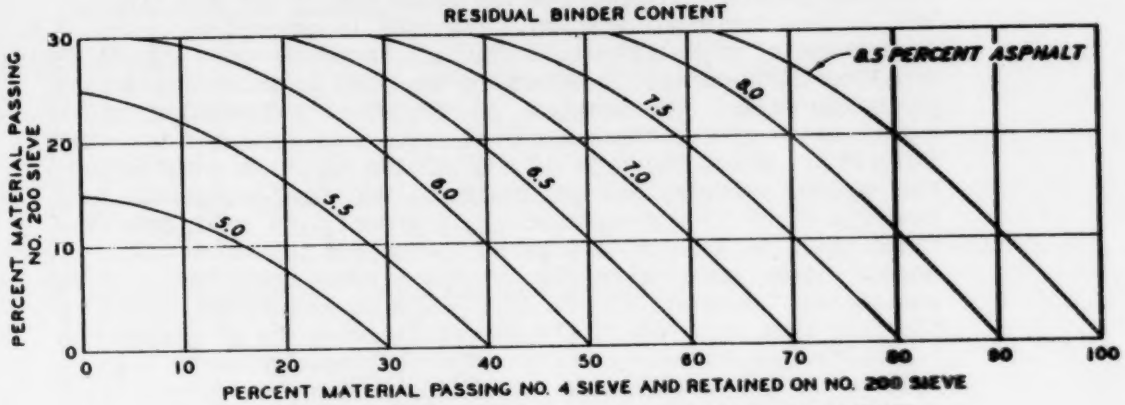
Table 18. Emulsified Asphalt Requirements

Percent Passing No. 200 Sieve	Pounds of Emulsified Asphalt per 100 Pounds of Dry Aggregate at Percent Passing No. 10 Sieve					
	≤ 50	60	70	80	90	100
0	6.0	6.3	6.5	6.7	7.0	7.2
2	6.3	6.5	6.7	7.0	7.2	7.5
4	6.5	6.7	7.0	7.2	7.5	7.7
6	6.7	7.0	7.2	7.5	7.7	7.9
8	7.0	7.2	7.5	7.7	7.9	8.2
10	7.2	7.5	7.7	7.9	8.2	8.4
12	7.5	7.7	7.9	8.2	8.4	8.6
14	7.2	7.5	7.7	7.9	8.2	8.4
16	7.0	7.2	7.5	7.7	7.9	8.2
18	6.7	7.0	7.2	7.5	7.7	7.9
20	6.5	6.7	7.0	7.2	7.5	7.7
22	6.3	6.5	6.7	7.0	7.2	7.5
24	6.0	6.3	6.5	6.7	7.0	7.2
25	6.2	6.4	6.6	6.9	7.1	7.3

FIGURE 18.

CLIMATIC ZONES	ASPHALT GRADE, PENETRATION
ARCTIC	100 TO 120
TEMPERATE	85 TO 100
TROPIC	60 TO 70
DESERT	40 TO 50

a. DETERMINATION OF ASPHALT GRADE FOR EXPEDIENT CONSTRUCTION



b. SELECTION OF ASPHALT CEMENT CONTENT

Selection of grade and quantity of asphalt cement

VII. SELECTION PROCEDURES FOR CHEMICAL STABILIZING ADDITIVES

A. Considerations

1. In selecting a stabilizer additive, one must consider the type of soil to be stabilized, the purpose for which the stabilized layer will be used, the type of soil quality improvement desired, the required strength and durability of the stabilized layer, the cost, and environmental conditions.

2. The soil gradation triangle in Figure19 is based upon the pulverization characteristics of the soil that, when combined with certain restrictions relative to the liquid limit(LL), the plasticity index(PI), and soil gradation contained in Table 19, provide guidance for the selection of the additive best suited for stabilization. Figure19 is entered with the percentage of gravel(#4-plus material), sand(#4-minus and #200-plus), and fines(#200-minus) to determine the area in which the soil gradation falls. The area(1A, 2B, 3C, etc.) indicated at the intersection of the three material percentages is used to enter Table 19 to select the type of stabilizing additive considering the various restrictions and remarks. For example, a soil having a PI of 15 and containing 67% gravel, 26% sand, and 7% fines falls in Area 2B of Figure19. Table 19 indicates that cement, lime, lime-cement-fly ash, or bitumen could be considered. However, the PI of 15 eliminates bitumen, and the fact that only 33% of the material passes the #4 sieve indicates that lime or a combination of lime-cement-fly ash will be the better additive for stabilization.

3. The next consideration in the selection of an additive will be the use of the stabilized layer. If it is only desired to modify the properties of the soil, such as to lower the PI and increase the % of fines, so that it would qualify as a subbase or base course material, lime may well be the best additive. If, however, high strengths and good durability are required to effect a reduction in pavement thickness, the use of a lime-cement or a lime-cement-fly ash combination may be the best additive. Actually, the best additive can only be determined by laboratory studies. However, laboratories aren't always available in a tactical situation. The next section will discuss expedient methods of additive selection. The success of additive stabilization depends, to a large extent, upon attaining complete and uniform distribution of the additive in the soil. This step is most critical when using bitumens or portland cement as additives. These materials work well in coarse-grained soils that pulverize more easily.

Generally, as the % fines and the PI increase, pulverization becomes more difficult and it is harder to obtain uniform distribution of the stabilizing additives. For these types of soils, preprocessing or pretreatment with other additives may be necessary. For example, fine-grained soils may be pretreated with lime to aid in their pulverization, making mixing of a bitumen or cement additive more successful.

FIGURE 19.

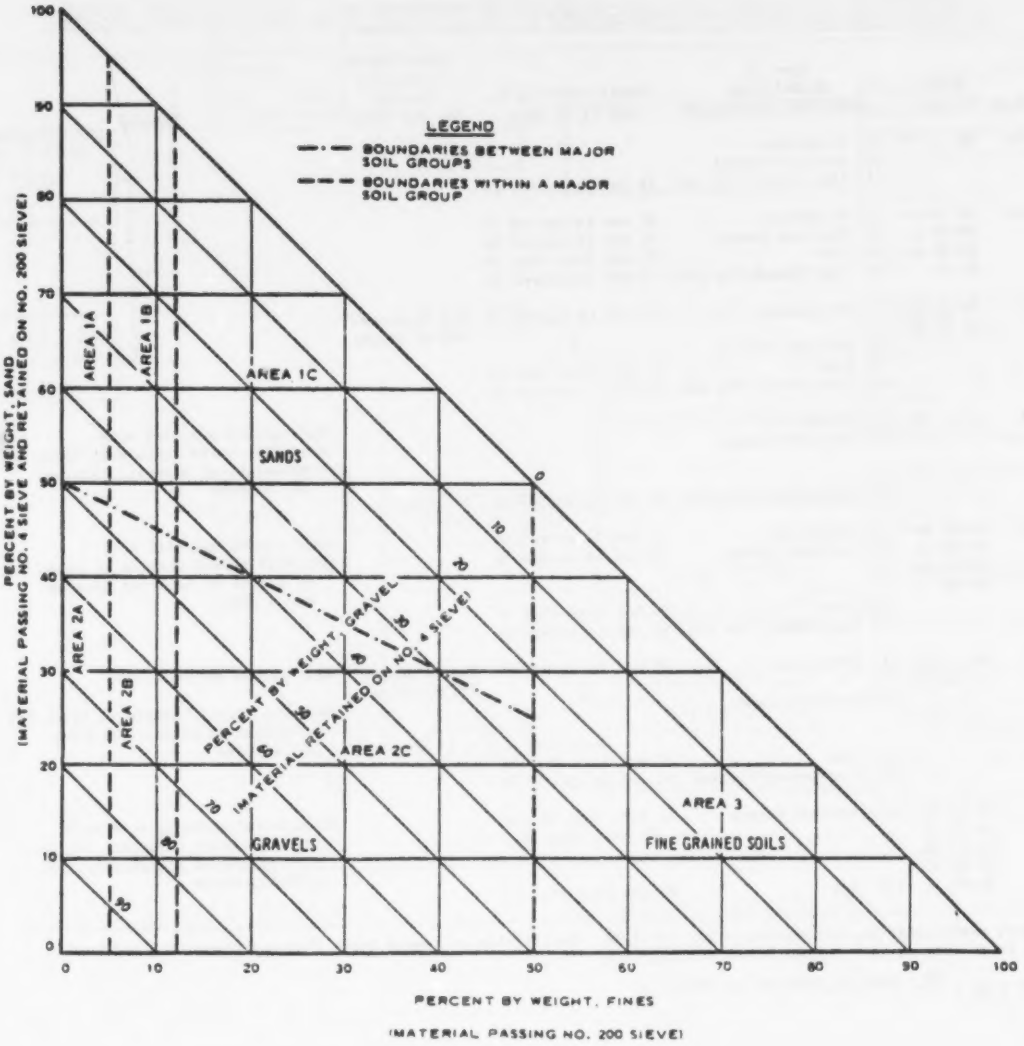

LEGEND
BOUNDARIES BETWEEN MAJOR SOIL GROUPS
BOUNDARIES WITHIN A MAJOR SOIL GROUP
AREA 1A
AREA 1B
AREA 1C
SANDS
AREA 2A
AREA 2B
AREA 2C
GRAVELS
AREA 3
FINE GRAINED SOILS
PERCENT BY WEIGHT, GRAVEL (MATERIAL RETAINED ON NO. 4 SIEVE)
PERCENT BY WEIGHT, SAND (MATERIAL PASSING NO. 4 SIEVE AND RETAINED ON NO. 200 SIEVE)
PERCENT BY WEIGHT, FINES (MATERIAL PASSING NO. 200 SIEVE)
0
10
20
30
40
50
60
70
80
90
100

TABLE 19. A GUIDE FOR DELIBERATE SELECTION OF A STABILIZING AGENT.

Area	Soils Class.[a]	Type of Stabilizing Additive Recommended	Restriction on LL and PI of Soil	Restriction on Percent Passing No. 200 Sieve[a]	Remarks
1A	SW or SP	(1) Bituminous (2) Portland Cement (3) Lime-Cement-Fly Ash	PI not to exceed 25		
1B	SW-SM or SP-SM or SW-SC or SP-SC	(1) Bituminous (2) Portland Cement (3) Lime (4) Lime-Cement-Fly Ash	PI not to exceed 10 PI not to exceed 30 PI not less than 12 PI not to exceed 25		
1C	SM or SC or SM-SC	(1) Bituminous	PI not to exceed 10	Not to exceed 30% by weight	
		(2) Portland Cement	----[b]		
		(3) Lime	PI not less than 12		
		(4) Lime-Cement-Fly Ash	PI not to exceed 25		
2A	GW or GP	(1) Bituminous (2) Portland Cement			Well-graded material only Material should contain at least 45% by weight of material passing No. 4 sieve
		(3) Lime-Cement-Fly Ash	PI not to exceed 25		
2B	GW-GM or GP-GM or GW-GC or GP-GC	(1) Bituminous (2) Portland Cement	PI not to exceed 10 PI not to exceed 30		Well-graded material only Material should contain at least 45% by weight of material passing No. 4 sieve
		(3) Lime (4) Lime-Cement-Fly Ash	PI not less than 12 PI not to exceed 25		
2C	GM or GC or GM-GC	(1) Bituminous	PI not to exceed 10	Not to exceed 30% by weight	Well-graded material only
		(2) Portland Cement	----[b]		Material should contain at least 45% by weight of material passing No. 4 sieve
		(3) Lime (4) Lime-Cement-Fly Ash	PI not less than 12 PI not to exceed 25		
3	CH or CL or MH or ML or OH or ML-CL	(1) Portland Cement	LL less than 40 and PI less than 20		Organic and strongly acid soils falling within this area are not susceptible to stabilization by ordinary means
		(2) Lime	PI not less than 12		

[a] Soil classification corresponds to MIL-STD-619B. Restriction on liquid limit (LL) and plasticity index (PI) is in accordance with Method 103 in MIL-STD-621A.

[b] PI $\leq$ 30 $\times$ $\frac{\text{50 - percent passing No. 200 sieve}}{\text{2}}$

FIGURE 20. AN EXPEDIENT GUIDE FOR SELECTING A STABILIZING AGENT

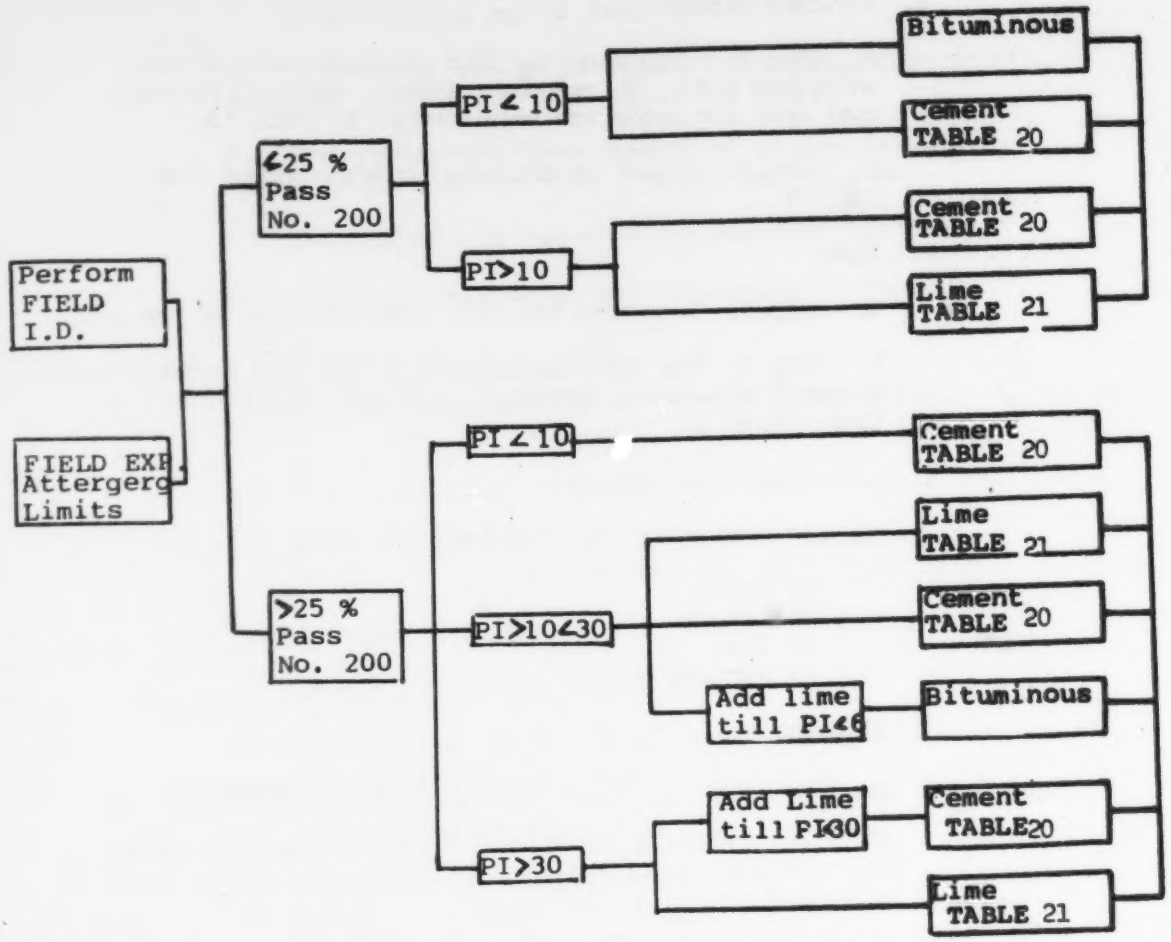


TABLE 20. ESTIMATED CEMENT REQUIREMENTS FOR VARIOUS SOILS

Soil Classification	Estimated Cement %
GM, SM, GC, SC	8%
CL, ML, CH	10%
MH, OH	11%

TABLE 21. ESTIMATED LIME REQUIREMENTS FOR VARIOUS SOILS

Soil Classification	Estimated Lime %
GC	4%
SM, SC, GM	10%
CL, CH	8%

B. EXPEDIENT METHODS OF CALCULATING ADDITIVE REQUIREMENTS

1. Portland cement

   a. Step 1: Determine the USCS classification of the untreated soil. In reduced thickness designs, the soil must meet the gradation requirements in Table 12.

   b. Step 2: Select an estimated cement content from Table 11.

2. Lime

   a. Step 1: Determine the USCS classification of the soil.

   b. Step 2: Use the Plasticity Index(PI) and percent binder(% of sub-#40 material) to select lime content from Figure 17.

3. Lime-cement-fly ash(LCF)

   The mix proportion for expedient LCF design will be:

   71% soil
   24% fly ash
   4% lime
   1% portland cement

4. Bituminous

   a. Determine the USCS classification and gradation.

   b. Check Tables 15 and 17 to determine if the soil meets the gradation requirements; if it doesn't, mechanically stabilize it.

   c. Use the gradation to determine the type of asphalt needed(SEE Table 16).

   d. Use the formula on page 71, Table 18, or Figure 18 to determine the amount of asphalt required.

5. Procedure for Estimating the Quantity of Stabilizing Agent Required.

a. Determine the soil type, Atterberg limits(PI), and dry density of the existing soil.

b. Determine the type and % of stabilizing agent requirements from Tables 20 and 21.

c. Determine the area to be treated (in ft^2).

d. Put the data into the following formula:

$$Q = A \times \frac{T}{12} \times D \times \frac{S}{100}$$

Q = total quantity of stabilizing agent required, in lbs.

A = area to be treated, in ft^2.

T = required thickness of stabilized layer, in inches, <u>for one lift only</u>.

D = dry density of the existing soil, in $\frac{lbs}{ft^3}$.

S = % treatment specified.

e. Divide the quantity of stabilizer required(lbs) by the weight of each bag (94 lbs for cement or 100 lbs for lime) to get the number of bags required for each lift.

f. Multiply the answer from step 5 by the number of lifts required, to get the total number of bags required for the project.

g. (OPTIONAL) Allow for a waste factor of 10% for dry areas or 15% for wet areas by multiplying step 6 by 1.10 or 1.15.

h. Determine the placement of the bags by the following formula:

$$\frac{\text{A (from step 3)}}{\text{\# of bags/lift (from step 5)}} = X^2 = \text{\#of } ft^2 \text{ per bag}$$

$$\sqrt{X^2} = x = \text{\# of feet between bags}$$

FIGURE 21. PREPARATION OF A SURFACE FOR IN-PLACE STABILIZATION

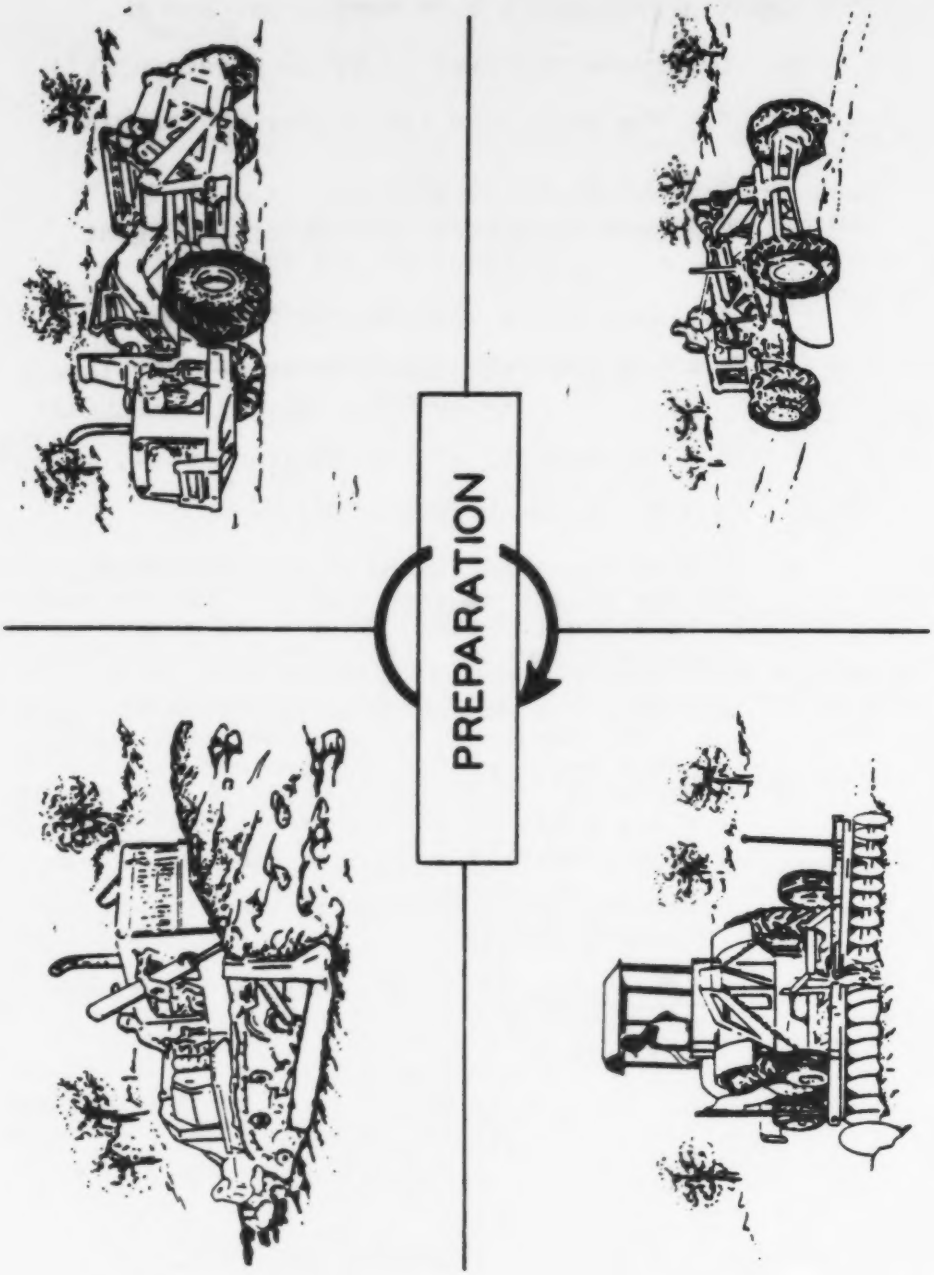


FIGURE 22. SPREADING STABILIZER

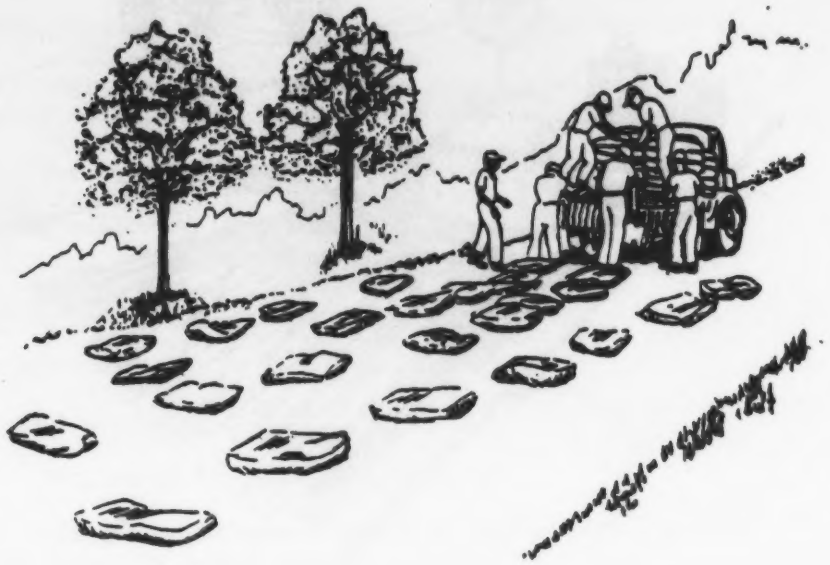


FIGURE 23. MIXING THE STABILIZER

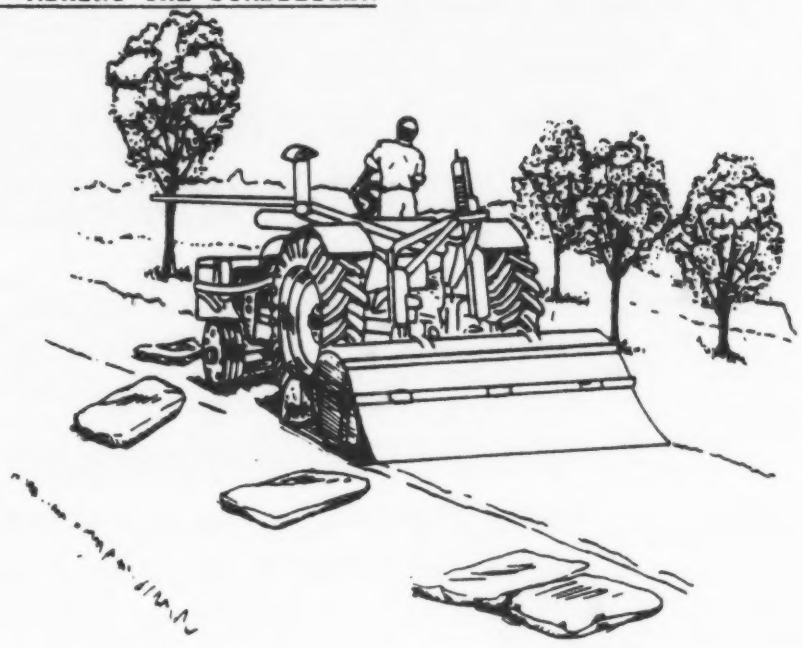
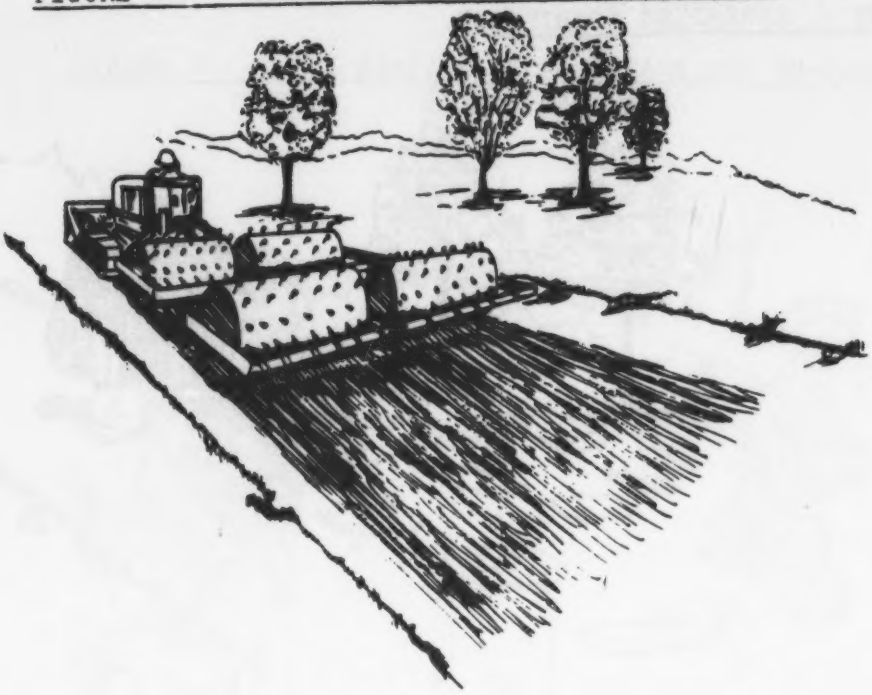


FIGURE 24. COMPACTION OF STABILIZED MATE...



A. Mechanical stabilization

1. Preparation

a. shape area to crown and grade.

b. scarify, pulverize, and adjust moisture content of the soil, if necessary. Remove any undesireable material such as roots, stumps, etc.

c. reshape to crown and grade.

2. Addition of deficient materials(if necessary)
Use one of the following methods:
a. distribute evenly with spreader(s).

b. use spreader box(es) behind dump truck(s)

c. tailgate measured truckloads to cover certain lengths.

d. dump in evenly spaced piles, grade into windrows, and then spread evenly.

3. Mixing

a. Add water, if required, to obtain a moisture content about 2% above OMC, and mix with a traveling mixer, a pulvimixer, a blade a scarifier, or a plow.

b. mix until soil and aggregate are a uniform well-graded mass.

c. reshape to proper crown and grade(if necessary).

4. Compaction

a. Begin compaction as soon as possible(within 4 hours) after adding water, to prevent water loss to evaporation.

b. Use sheeps-foot roller, pneumatic roller, or crawler-type tractor for initial compaction; finish with steel-wheel roller or lightweight pneumatic roller.

B. Cement stabilization

1. Preparation -See para. A.1 above.

2. Cement spreading

Use one of the following methods:

a. place bags of cement on the ground, empty the bags, and level the cement with a rake or drag.

b. apply bulk cement from self-unloading trucks(bulk trucks) or from dump trucks with spreaders.

3. Mixing

a. add water and mix with either a single-shaft mixer or a multiple-shaft mixer.

b. mixing can be performed by processing in 6' to 8' wide passes(the width of the mixer) or by mixing in a windrow.

c. mix and pulverize until all of the soil-cement mixture will pass a 1" screen and at least 80% will pass a #4 sieve, excluding any gravel or stone.

4. Compaction

a. begin IMMEDIATELY after final mixing; otherwise the cement may hydrate before compaction is completed.

b. use pneumatic-tired and sheeps-foot rollers; finish the surface with steel-wheeled rollers.

5. Curing. Apply a bituminous material at a rate of 0.15 to 0.30 gallons per square yard, or cover the area with about 2 inches of soil or thoroughly wetted straw.

C. Lime stabilization

1. Preparation

a. shape surface to crown and grade

b. scarify to specified depth

c. partially pulverize the soil

d. remove all organic material and soil/aggregate particles larger than 3 inches.

2. Lime spreading - Apply about ½ of the total lime required by one of the following methods.
a. place bags of lime on the area, empty them, and level the lime with rakes or drags.

b. apply bulk lime from self-unloading(bulk) trucks or from dump trucks with spreaders.

c. apply the lime by slurry, with 1 ton of lime per 500 gallons of water. The slurry can be mixed in a central plant or in a tank truck and can be distributed by standard water or asphalt tank trucks with or without pressure.

3. Preliminary mixing, watering, and curing (only required when stabilizing highly plastic clays)
a. mix lime and soil (pulverize the soil to sub-2" particle size, excluding any gravel or stone).

b. add water (Caution: Soil moisture content should only be increased by about 2%)

c. mix the lime, soil, and water using blades or rotary mixers

d. shape the lime treated layer to the appropriate size

e. compact lightly to minimize evaporation loss, lime carbonation, or excessive wetting from heavy rains.

f. cure the lime-soil mixture for up to 48 hours to permit the lime and water to break down any clay clods. For extremely plastic clays, the curing period may be extended to 7 days.

4. Final mixing and pulverization

a. add remaining lime by an appropriate method

b. continue mixing and pulverizing until all of the clods are broken down to pass a 1" screen and at least 60% of the material will pass a #4 sieve.

D. Bituminous stabilization

1. In-place stabilization using bituminous materials can be performed with a traveling plant mixer, a rotary type mixer, or a blade. The methods for using these mixers are outlined below.

a. Traveling plant mixer.

(1) Preparation
(a) the surface on which the mixed material is to be placed must be shaped and compacted.
(b) a prime coat is applied to the surface and allowed to cure.
(c) excess asphalt from the prime coat should be blotted with a light application of dry sand.

(2) Aggregate is brought to the site and windrowed by dump trucks, spreaders/spreader boxes, or blades.

(3) Asphalt is added to the windrows by an asphalt distributor truck or within the traveling plant mixer.

(4) The material is mixed with any of several types of single-shaft or multiple-shaft mixers.

(5) The mixture is aerated by working it, often with a blade, until about 50% of the volatiles in it have evaporated.

(6) Spread the material to uniform grade and desired shape.

(7) Compact to proper density.

b. Rotary mixer

(1) Prepare the surface as in 1. a. (1) above.

(2) Spread the aggregate to uniform grade and appropriate cross-section.

(3) Mix the aggregate by one or more passes of the mixer.

(4) Add asphalt in increments of about 0.5 gallons per square yard and mix. The asphalt can be mixed with the mixer or with a distributor truck.

(5) Make one or more passes with the mixer after each addition of asphalt.

(6) Maintain the surface at grade and cross-section by using a blade during the mixing operation.

(7) Aerate the mixture.

c. Blade mixing

(1) Prepare the surface as above.

(2) Place the material in a windrow.
(3) Apply asphalt to a flattened windrow with a distributor truck; it is best to use multiple applications of asphalt.
(4) Mix thoroughly with a blade.
(5) Aerate the mixture.
(6) Move the mixed windrow to one side of the road.
(7) Spread the mixture to the proper grade and crown.
(8) Compact the mixture to the appropriate density.

2. Central-plant construction. Although central-plant mixing is desireable in terms of the overall quality of the stabilized soil, it is not often used for T/O construction. Stabilization with asphalt cement, however, must be accomplished with a central hot-mix plant. The construction methods for central plant mixing that are common for use with all types of stabilizers are given below:

a. Materials storage areas must be prepared for soils and aggregates, stabilizer, and water.

b. Mixing area must be set up to receive materials and mix.

c. Trucks must be available for hauling.

d. Spreaders, spreader boxes, or bottom-dump trucks must be available for placing the material at a uniform thickness.

e. Compact the material with the appropriate roller type.

f. Provide the correct materials to aid in curing.

3. Surface waterproofing

a. Preparation

(1) Shape area to crown and grade.
(2) Remove unsuitable material such as vegetation and any jagged soil-aggregate particles.

b. Mixing

(1) Adjust the water content to between OMC and OMC-2%, and mix.
(2) Blade to grade and crown.

c. Compaction

(1) Begin after mixing.
(2) Use pneumatic or sheeps-foot rollers.

d. Membrane placement

(1) Blade the area to grade and crown and cut anchor ditches. using a motor grader.
(2) Roll area with steel-wheel or light pneumatic roller.
(3) Place neoprene-coated nylon or polypropylene asphalt membran

IX. PRACTICAL EXERCISES

1. A site investigation for a proposed airfield produced the soil characteristics of soil A. A possible borrow site had the soil characteristics of soil B. These two soils are to be mechanically stabilized to produce a base course material. Determine the characteristics of the final mix.

Sieve Size[1]	Soil A[2]	Soil B[3]
2"	100	100
1½"	62	75
1"	50	59
3/4"	44	55
3/8"	32	49
#4	21	39
#10	12	23
#40	3	16
#200	1	2
LL	8	16
PL	5	11

SIEVE SIZE 1	PERCENT PASSING				$\lvert\bar{S}-A\rvert$ (5-1)	$\lvert\bar{S}-B\rvert$ (5-2)	%A 6	%B 7	PERCENT PASSING, FINAL MIX (4+7)
	SOIL A 2	SOIL B 3	SPEC'S S 4	$\bar{S}$ 5					
LL					Σ_A	Σ_B			
PL									
PI									

2. The surface course for a proposed road linking two divisions is to be constructed from material from a sand bar and an alluvial terrace. What is the final mix gradation and Atterburg limits?

Sieve Sizes[1]	Sand Bar[2]	Alluvial Terrace[3]
1"	100	100
3/4"	95	80
3/8"	90	51
#4	75	39
#10	63	22
#40	54	13
#200	33	4
LL	40	12
PL	30	8

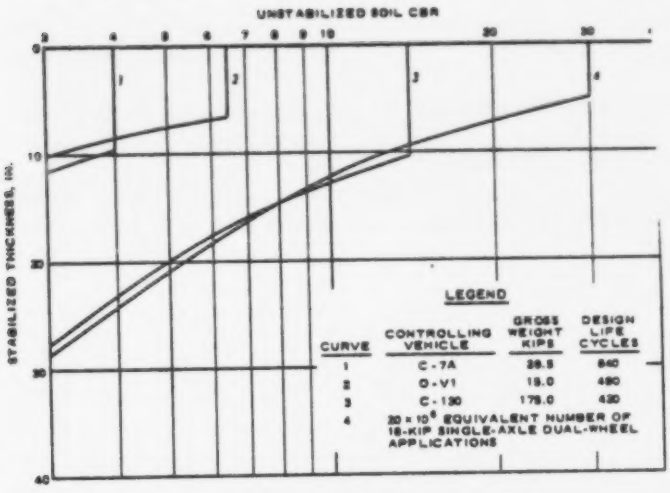
SIEVE SIZE 1	PERCENT PASSING: SOIL A 2	SOIL B 3	SPEC'S S 4	$\bar{S}$ 5	$\lvert\bar{S}-A\rvert$ (5-1)	$\lvert\bar{S}-B\rvert$ (5-2)	%A 6	%B 7	PERCENT PASSING, FINAL MIX (6+7)
LL					Σ_A	Σ_B			
PL									
PI									

3. A unit is assigned the mission of quickly providing an expedient road between two organizational units. Only the in-place material can be stabilized. The preliminary site investigation indicates that the soil has a natural strength of 15 CBR, a liquid limit of 30, and a plasticity index of 15 and that 55 percent of the material passes the No. 200 sieve. The soil classifies as a CL material according to the USCS. Only cement, emulsified asphalt, are readily available. Determine type and amount of stabilizer to use and thickness of stabilized layer.

4. A unit is given the mission of providing a road between two organizational task forces. The preliminary site investigation indicates a soil strength of 10 CBR, 80 percent of the material passing the No. 4 sieve, 50 perfent passing the No. 40 sieve, 20 percent passing the No. 200 sieve, and a plasticity index of 12. Only lime and cutback asphalt are available. Determine type and amount of stabilizer to use.

5. A unit is to provide an expedient airfield capable of withstanding 0-V1 aircraft traffic. The preliminary site investigation indicates that the soil classifies as GM according to the USCS and has a natural soil strength of 23 CBR and that drainage conditions are satisfactory. The extended weather forecast indicates that rain can be expected 50 percent of the time for the next 60 days. Determine proper procedures for insuring that this airfield will remain operational.

FIGURE 25.



Road and airfield design curves for stabilized soils in forward areas

SOILS EXPLORATION

REFERENCE: TM 5-330,CH 2,Sect IV

Establish a Testing Program.

The engineer will direct the soils analyst as to where to establish test pits and as to which tests to perform. The following tests should be considered for every subgrade stratum that may have an effect on the design of a road or airfield, as well as for every potential borrow pit soil.

A. Mandatory for horizontal construction planning and design.

1. Sieve analysis.
2. Moisture content determination.
3. Standard compaction test.
4. Liquid and plastic limit determination.
5. CBR testing and analysis.

B. Optional for horizontal construction-

1. Specific gravity.
2. Hydrometer analysis.
3. Unconfined compression testing.
4. Stabilization testing.

EXPLORATION SAFETY

Explorations require test pits and bore holes to be developed for subsurface investigation. Before, during and after an excavation is complete, the following guidelines should be adhered to to insure jobsite safety.

SAFETY REQUIREMENT CHECKLIST

1. Have underground utilities been located, and utility companies notified before the excavation begins?
2. Are surface hazards such as trees and boulders removed or made safe?
3. Is protective equipment provided for all personnel?
4. Insure that personnel are always kept clear from overhead loads.
5. Have the slopes been made stable?
6. If required, have shoring supports been installed? Personnel should never enter a pit deeper than shoulder level without shoring!!
7. Insure that all excavated or stored materials are placed at least two feet from the edge of the excavation.
8. Have exit ladders or steps been provided for personnel working in the excavation?
9. Insure that the excavation is inspected daily and after every rainstorm or other hazard-increasing occurrence.
10. Insure that once the excavation is complete the trenches are backfilled and the supports are removed simultaneously.

C A I

C A I

GRADATION CRITERIA

	GRAVEL PREDOMINANT	SAND PREDOMINANT
Cu	>4	>6
Cc	1–3	1–3

MUST MEET BOTH CRITERIA

THEORY OF COMPACTION

PLASTICITY INDEX	TYPE OF FINES	COMPACTIVE EFFORT
≥ 5	Cohesive	90–95 %
≤ 5	Cohesionless	95–100 %

QUALITY CONTROL PROGRAM

GUIDELINES FOR ROADS AND AIRFIELDS TESTING

- TEST EVERY LIFT .... AS SOON AS ALL COMPACTION IS COMPLETED
- TEST EVERY 100 FT .... SAND CONE/SPEEDY = 1 TEST
  NUCLEAR METHOD = 3 TESTS, TAKE AVERAGE
- STAGGER TESTS ALONG THE CENTER LINE
- UTILIZE A "TEST STRIP" .... TO DETERMINE # OF PASSES REQUIRED

CORRECTIVE ACTIONS

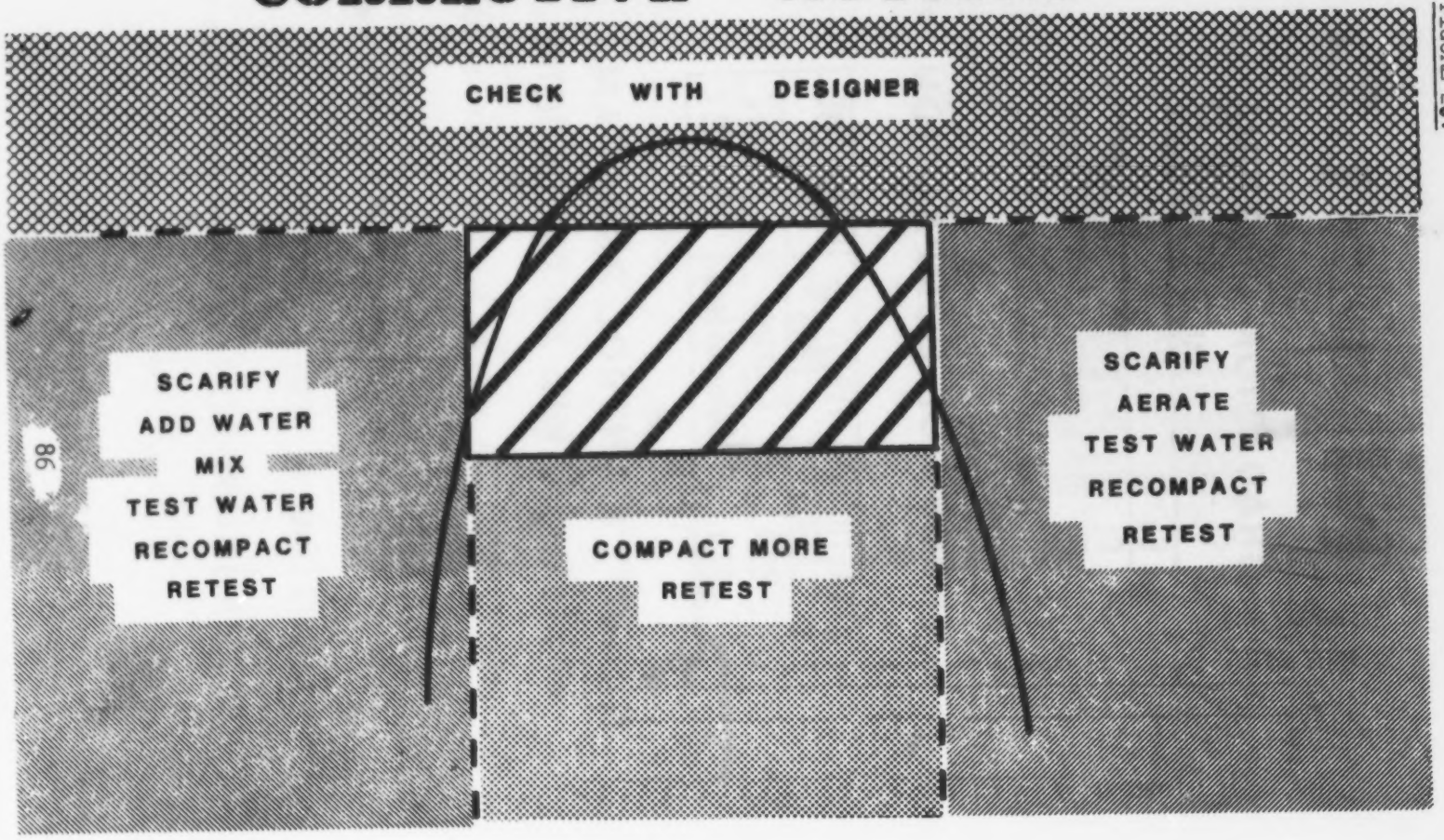
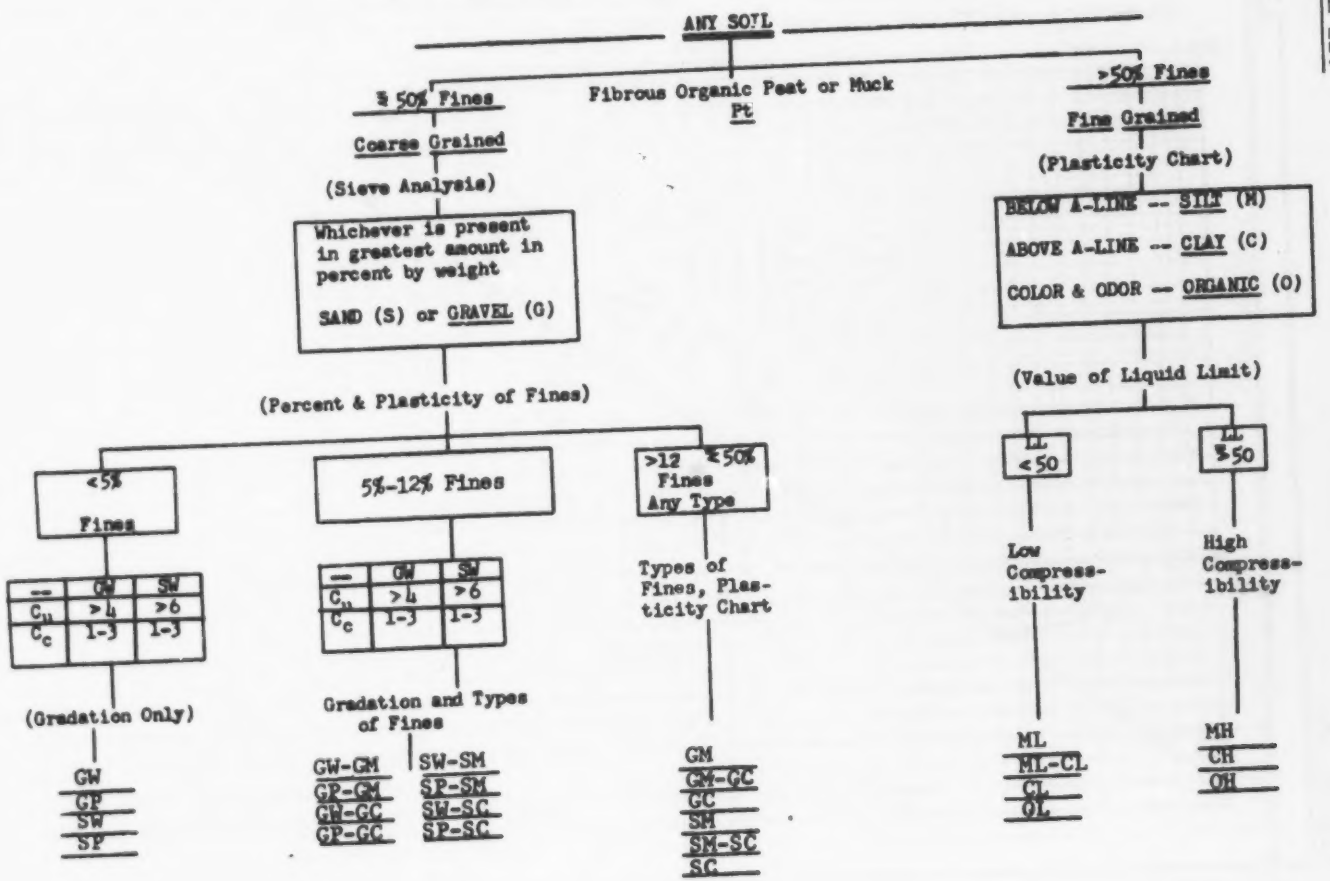
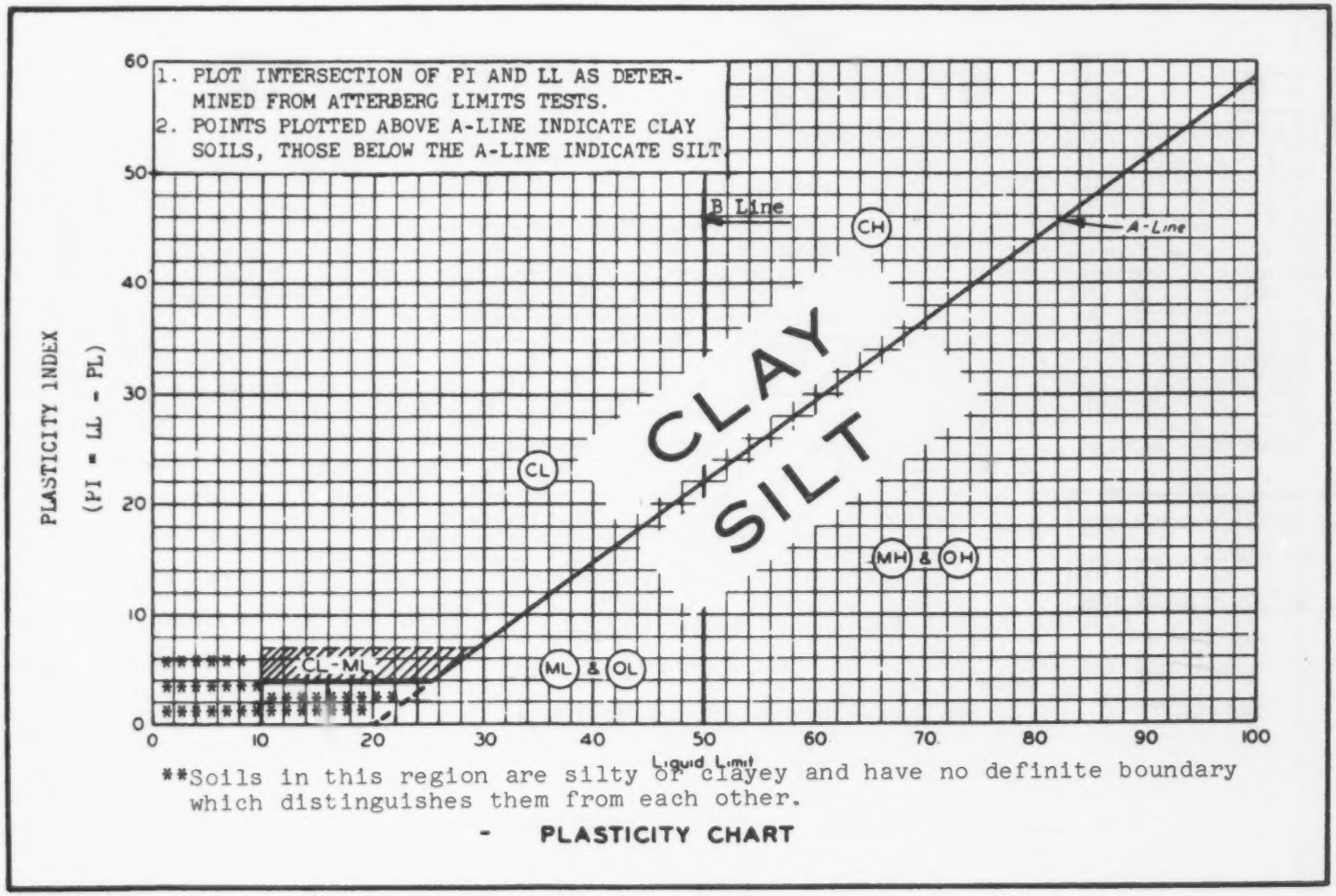


FIGURE 26.

TABLE 22.

CLASSIFICATION PROCEDURE (Schematic)





**Soils in this region are silty or clayey and have no definite boundary which distinguishes them from each other.

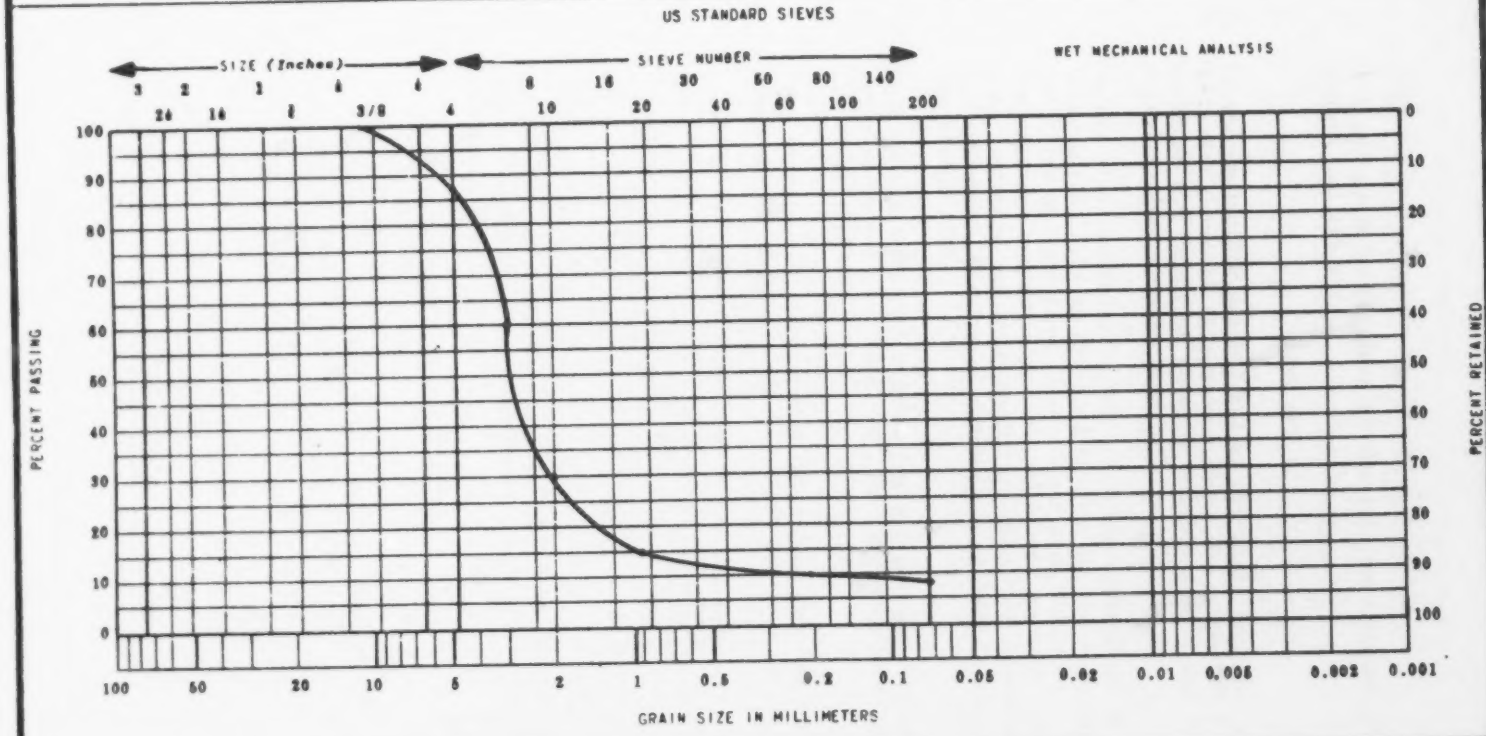
- PLASTICITY CHART

FIGURE 27.

GRAIN SIZE DISTRIBUTION GRAPH - AGGREGATE GRADING CHART

DATE

PROJECT


US STANDARD SIEVES
SIZE (Inches)
SIEVE NUMBER
WET MECHANICAL ANALYSIS
3 2 1 4 3/8 4 8 16 30 50 80 140
24 14 8 10 20 40 60 100 200
PERCENT PASSING
PERCENT RETAINED
100 90 80 70 60 50 40 30 20 10 0
100 50 20 10 5 2 1 0.5 0.2 0.1 0.05 0.02 0.01 0.005 0.002 0.001
GRAIN SIZE IN MILLIMETERS

EXCAVATION NUMBER	SAMPLE NUMBER	NATURAL % MOISTURE	w_L	w_P	I_P	CLASSIFICATION	REMARKS
TECHNICIAN (Signature)			PLOTTED BY (Signature)				CHECKED BY (Signature)

DD, FORM 1 AUG 57 1207

GPO 931160

FIGURE 20.

U.S. GOVERNMENT PRINTING OFFICE: 1985-461-663/20326

STUDENT NOTES

SOLUTIONS TO PRACTICAL EXERCISES

#1. (p.35)

a. What CBR would be obtained if the soil were placed at 15% moisture content and 135 pcf?

CBR = 8.1

b. If the design CBR established in the class exercise were used to determine pavement thicknesses above the compacted subgrade, what would be the impact on pavement performance if the soil were placed as described in item "a"?

In the class exercise, a CBR = 9.2 was designated as the design value which could be obtained by placing the soil between 120.9 and 127.4 pcf and from 11 to 15 per cent moisture. In item "a", the moisture content range was achieved; however, the soil was over compacted and a strength less than that required by the design was achieved. The result could be a failure of the subgrade under the design load.

c. What is the impact of stipulating a 3 per cent moisture range (some value $\pm$ 1½ per cent) for the same density ranges used in the class problem?

From step No. 2 , the assured CBR values for the specified density range are as follows:

w	CBR	w	CBR
10	8.5	15	10.3
11	9.2	16	7.4
12	10.0	17	5.4
13	11.3	18	4.2
14	13.6		

As was done in step No. 3 , the CBR values for potential moisture content ranges will be determined. This time, the moisture ranges are as follows:

w(range)	CBR	
10-13	8.5	
11-14	9.2	
12-15	10.0	Design CBR
13-16	7.4	
14-17	5.4	
15-18	4.2	

The best assured CBR occurs at 12-15 per cent moisture and has a value of 10. Thus if the engineer were willing to live with the difficulties associated with getting the soil placed with this 3 per cent range, he could count on a slightly higher CBR and a reduced pavement thickness. The question arises as to whether or not the benefit is worth the trouble. The decision depends mainly on the judgment of the engineer. He must consider such factors as:

1) Savings in materials
2) Experience of on-the-job supervisors
3) Availability and ability of quality control personnel
4) Weather conditions

The final analysis amounts to determining whether or not the cost of materials saved is greater than the cost to place the soils under the more restrictive conditions.

d. What is the design CBR for densities of 90 to 95 per cent of maximum CE 55 dry density and a 4 per cent moisture content specification range?

Step #1 At 90 - 95% max CE 55, density range is 117.0 to 123.5 pcf.

Step # 2

w	CBR	w	CBR
10	7.2	15	11.4
11	7.7	16	8.3
12	8.2	17	6.3
13	9.2	18	4.8
14	10.6		

Step # 3

w(range)	CBR
10-14	7.2
11-15	7.7
12-16	8.2
13-17	6.3
14-18	4.8

Step # 4 Design CBR = 8.2
@12 - 16% moisture and 90 - 95% of max. CE 55 dry density

#2. (p. 35 and 38)

The following information was obtained from the CBR Family of Curves.

Moisture Content % w	Corrected CBR in %
10	6.6
11	7.6
12	8.9
13	9.5
14 (OMC)	10.5
15	11.4
16	8.5
17	5.4
18	3.0

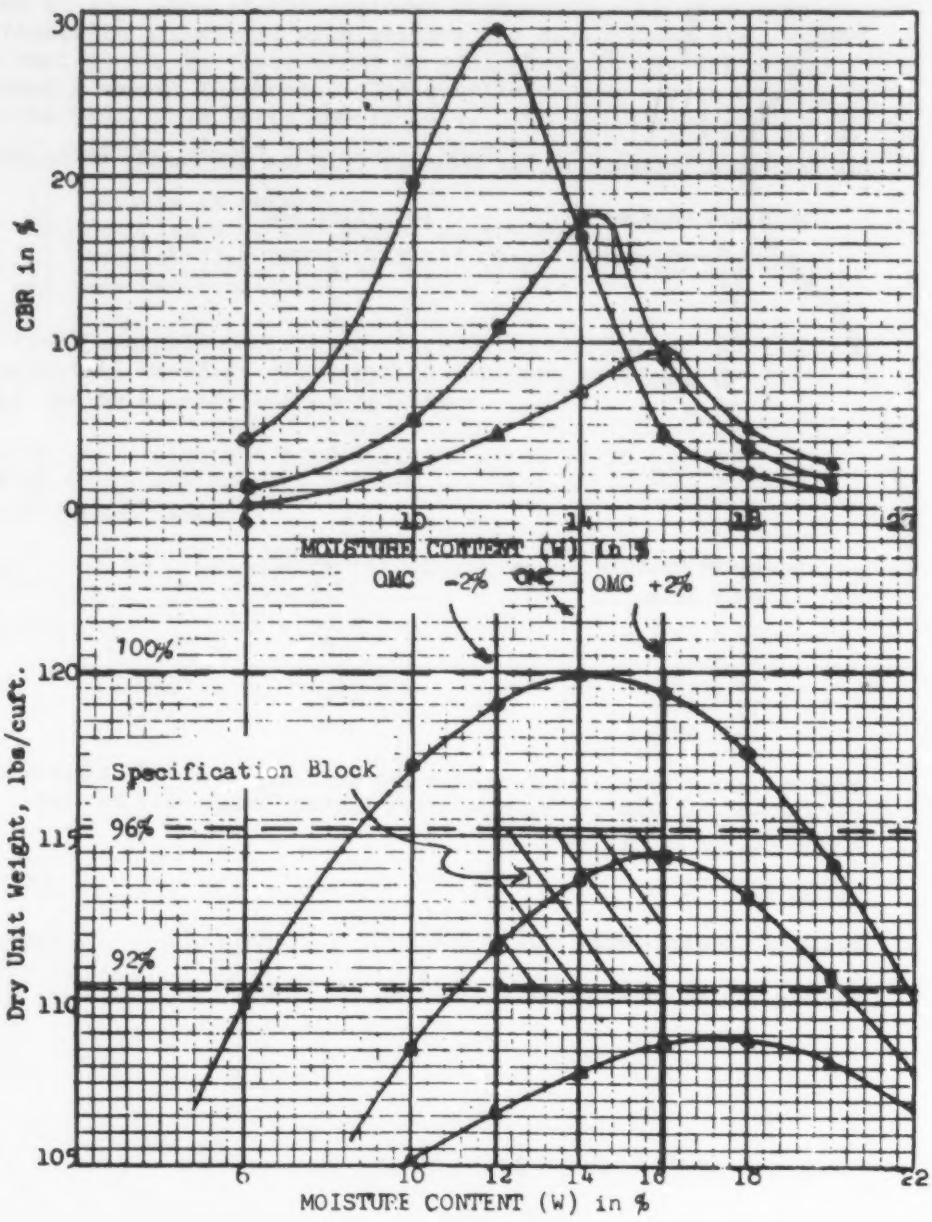
Moisture Content Range in %	Corrected CBR in %
10 - 14	6.6
11 - 15	7.6
12 - 16	8.5
13 - 17	5.4
14 - 18	3.0

From the above tabulated data, the design CBR will be the largest of the CBR values, and the best moisture content range will be that producing the design CBR.

Design CBR = 8.5%

Moisture Content Range = 12 - 16%

The Specification Block is plotted on the compaction curve.



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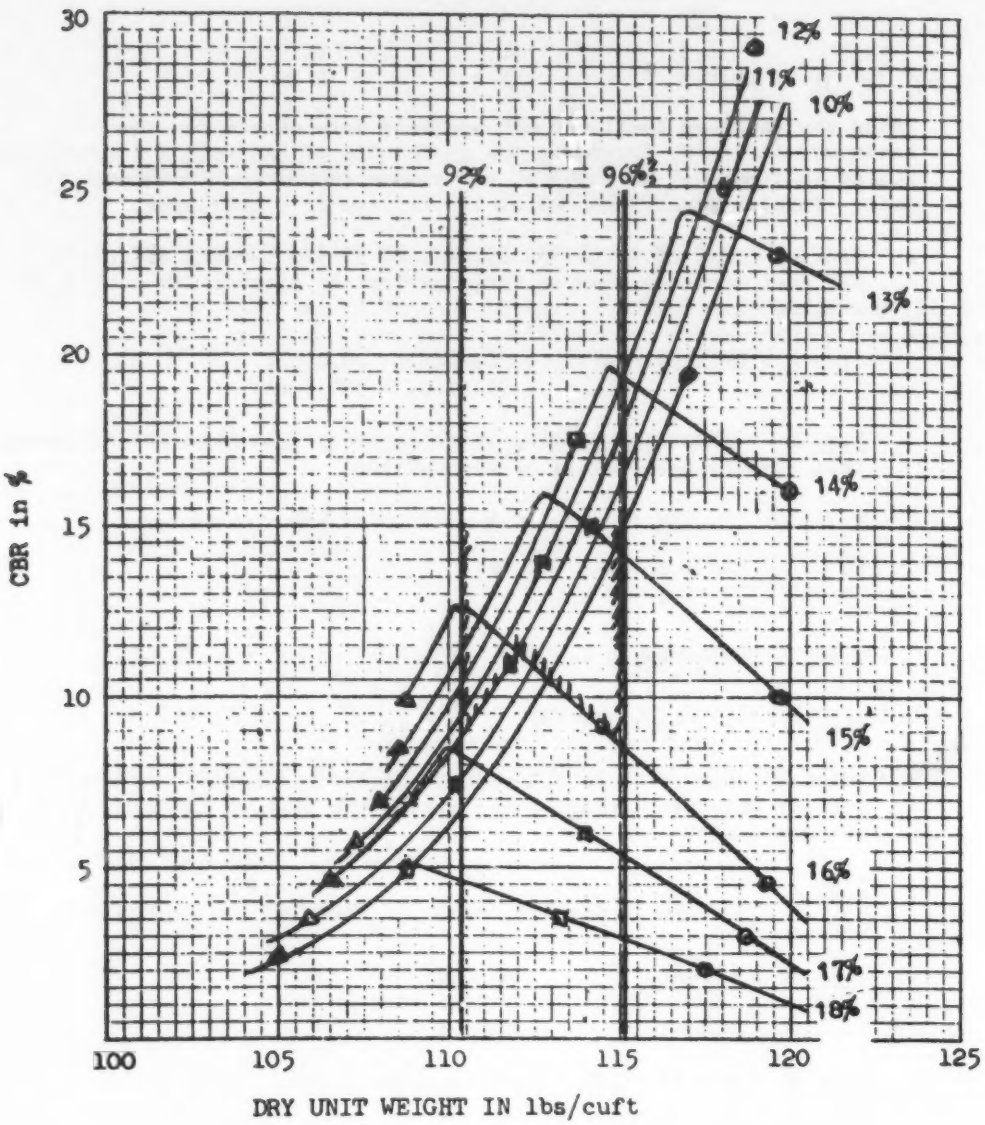
CBR FAMILY OF CURVES



#3. (p. 35 - 36)

Using the attached swell and CBR analysis data sheets for the Karlsruhe Airfield, determine the design CBR of the soil for conditions stated in items "a" through "e" and answer questions "f" through "h". Note: Samples were compacted at 12, 26, and 55 blows/layer.

a. Density range of 90 to 95% of max. CE 55 dry density and the 4 per cent moisture content range giving the highest CBR with 3 per cent or less swell.

Step 1 - Density range: (.90)(110) = 99.0 pcf
(.95)(110) = 104.5 pcf

Step 2 - Eliminate molding water contents less than 17% to insure that objectionable swell is not obtained

w	CBR	w	CBR
17	3.4	20	2.6
18	3.5	21	1.8
19	4.1		

Step 3 - w(range) 17 - 21 CBR 1.8 (design CBR)

Step 4 - w = 17 - 21%, γ_d = 99 - 104.5 pcf

b. Density range of 90 to 95% of max. CE 55 dry density and the 3 percent moisture content range giving the highest CBR with 3 per or less swell.

Step 1 -
Step 2 - } Same as Steps 1 and 2 of Item "a".

Step 3 - w(range) 17 - 20 CBR 2.6 (design CBR)
18 - 21 1.8

Step 4 - w = 17 - 20%, γ_d = 99 - 104.5 pcf

c. Density range of 91 to 96% of max. CE 55 dry density and the 4 per cent mointure content range giving the highest CBR with 3 per cent or less swell.

Step 1 - Density range: (.91)(110) = 100.1 pcf
(.96)(110) = 105.6 pcf

Step 2 -

w	CBR	w	CBR
17	3.8	20	2.4
18	4.0	21	1.7
19	3.9		

Step 3 - w(range) 17 - 21 CBR 1.7 (design CBR)

Step 4 - w = 17 - 21%, γ_d = 100.1 - 105.6 pcf

d. Density range of 91 to 96% of max. CE 55 dry density and the 3 per cent moisture content specification range giving the highest CBR with 3 per cent or less swell.

Step 1 - } Same as Steps 1 and 2 in Item "c".
Step 2 - }

Step 3 -

w(range)	CBR	
17 - 20	2.4	(design CBR)
18 - 21	1.7	

Step 4 - w = 17 - 20%, γ_d = 100.1 - 105.6 pcf

e. Density range of 90 to 95% of max. CE 55 dry density and the 4 per cent moisture content specification range giving the highest CBR. Consider all moisture contents given on the CBR family of curves.

Step 1 - 99.0 - 104.5 pcf

Step 2 -

w	CBR	w	CBR
13	2.6	18	3.5
14	2.8	19	4.1
15	3.0	20	2.6
16	3.1	21	1.8
17	3.4		

Step 3 -

w(range)	CBR	
13 - 17	2.6	
14 - 18	2.8	
15 - 19	3.0	(design CBR)
16 - 20	2.6	
17 - 21	1.8	

Step 4 - w = 15 - 19%, γ_d = 99.0 - 104.5 pcf

f. From the results of items "a" and "c", how does increasing compaction affect the design strength of the soil?
It decreases the design strength.

g. How is the design strength of the soil affected by including swell in the analysis? Explain.
For this soil, the design strength is decreased from 3 to 1.8. Elimination of the potential moisture contents less than 17 per cent also eliminated the conditions at which a maximum design strength could be achieved thus illustrating that the technique of analysis for an expansive soil sacrifices strength for assurance that three per cent swell or less is obtained.

h. Do you consider the amount of data (i.e ranges of moisture content and levels of laboratory compactive effort) adequate for determination of a design CBR? Explain.
Yes. As this is a soil having a CBR less than 20, and the level of required field compaction is only greater than 90% of max. CE 55 densities, the 12, 26, and 55 blow/layer compactive efforts simulate the potential practical field placement levels adequately. The moisture content range of OMC $\pm$4% includes the peak strength at each level of compactive effort and allows for determination of the minimum CBR within a realistic moisture content specification range.

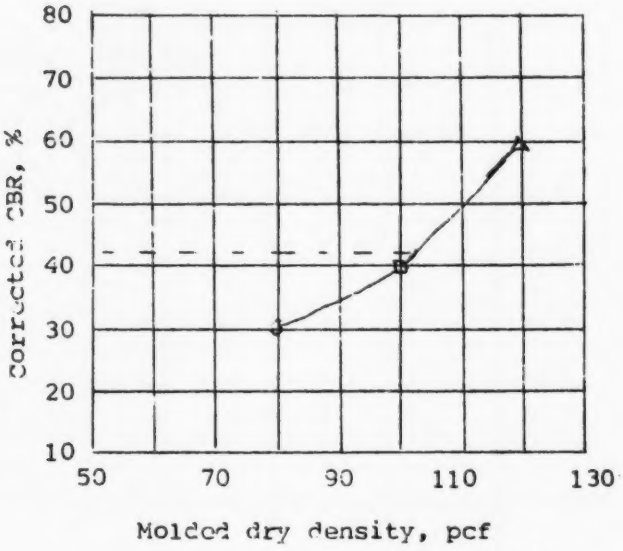
#4. (p. 37)
Using the attached data for the "Mason's Pit", answer the following questions:

a. Does this soil possessthe properties which allow for testing and analysis as a free draining soil? How can you tell? Yes. From the shapes of the compaction curves. They display limiting moisture content.

b. What is the design CBR of this soil for 102 to 107% of max. CE 55 dry density.

Density range: (100)(1.02) = 102 pcf
(100)(1.07) = 107 pcf

Design CBR = 42%



c. What placement moisture content specification would you impose to achieve the design CBR?
As minimum field placement is somewhat greater than 100% of max. CE 55 dry density, the minimum amount of moisture required is slightly less than 15% but more than 14%. To be safe, stipulate 15% or greater.

d. What is the minimum level of compactive effort required by Corps specification and why is this limit imposed? Minimum is 100% of max. CE 55 dry density. This is imposed to eliminate settlement problems.

#1. (p. 79)

SIEVE SIZE 1	PERCENT PASSING: SOIL A 2	SOIL B 3	SPEC'S S 4	$\bar{S}$ 5	$\lvert\bar{S}-A\rvert$ (5-1)	$\lvert\bar{S}-B\rvert$ (5-2)	0.278 A 6	0.722 B 7	PERCENT PASSING, FINAL MIX (6+7)
2"	100	100	100	100	0	0	27.8	72.2	100.0
1.5"	62	75	70-100	85	23	10	17.2	54.2	71.4
1"	50	59	55-85	70	20	11	13.9	42.6	56.5
3/4"	44	55	50-80	65	21	10	12.2	39.7	51.9
3/8"	32	49	30-60	45	13	4	8.9	35.4	44.3
#4	21	39	20-50	35	14	4	5.8	28.2	34.0
#10	12	23	15-40	27	15	4	3.3	16.6	19.9
#40	3	16	5-25	15	12	1	0.8	11.6	12.4
#200	1	2	0-10	5	4	3	0.3	1.4	1.7
					$\sum_A = 122$	$\sum_B = 47$			

$\frac{A}{B} = \frac{122}{47} = 2.60 \Rightarrow A = 2.60\,B \Rightarrow$ 1 part A = 2.6 part B $\Rightarrow$ $A = \frac{1}{3.6} = 0.278$, $B = \frac{2.6}{3.6} = 0.722$

#2. (p. 80)

SIEVE SIZE 1	PERCENT PASSING: SOIL A 2	SOIL B 3	SPEC'S S 4	$\bar{S}$ 5	$\lvert\bar{S}-A\rvert$ (5-1)	$\lvert\bar{S}-B\rvert$ (5-2)	0.721 A 6	0.279 B 7	PERCENT PASSING, FINAL MIX (6+7)
1"	100	100	100	100	0	0	72.1	27.9	100.0
3/4"	95	80	85-100	93	2	13	68.5	22.3	90.8
3/8"	90	51	65-100	83	7	32	64.9	14.2	79.1
#4	75	39	55-85	70	5	31	54.1	10.9	65.0
#10	63	22	40-70	55	8	33	45.4	6.1	51.5
#40	54	13	25-45	35	19	22	33.9	3.6	42.5
#200	33	4	10-25	18	15	14	23.8	1.1	24.9
					$\sum_A = 56$	$\sum_B = 145$			

$\frac{A}{B} = \frac{56}{145} \Rightarrow B = 2.59\,A \Rightarrow$ 1 part B = 2.59A $\Rightarrow$ $B = \frac{1}{3.59} = 0.279$ $A = \frac{2.59}{3.59} = 0.721$

#3. (p. 81)

CBR = 15
LL = 30
PI = 15
USCS: CL
55% passes #200

Entering figure 19 with % fines, the point plots somewhere in Area 3. Table 19 denotes that only lime and portland cement can be used. Only cement is available and PI is less than than 12. Table 20 indicates to use 10% portland cement. Entering figure 25 at CBR of 15 and intersecting curve #4 gives stabilization of 9".

#4. (p. 81)

CBR = 10
PI = 12
80% passes #4
50% passes #40
20% pases #200

Percent that passes #4 and retained on #200 is 80-20 = 60%. Entering Figure 19 with 60% and 20%, plots in Area 1C. Table 19 denotes four materials to use. However, only lime and cutback asphalt are available and PI is greater than 10 so lime is used. Entering figure 17 with PI of 12, and 50% passing #40 gives lime content of 12%.

#5. (p. 81)

From a study of the design curve for O-V1 aircraft (Figure 25), it can be seen that a 23-CBR soil strength is adequate. However, a reduction in strength can be anticipated due to the predicted rainfall.

A serviceable airfield can be constructed on this site and expected to remain operable during the predicted rainfall if (a) the site is shaped to the proper crown and grade, (b) an adequate drainage system is provided, and (c) the surface of the airfield is waterproofed.

Because of the aggregate or coarse-grained natural soil, a single or multiple asphalt surface treatment should be applied to waterproof the airfield.

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